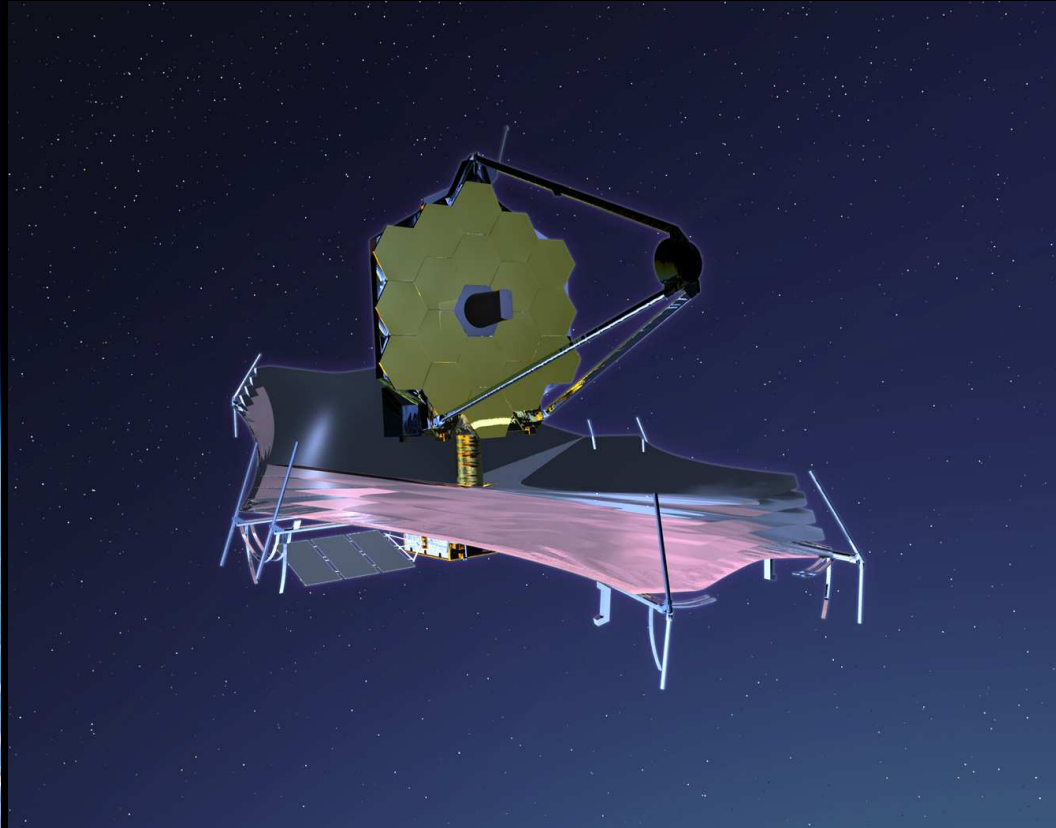


Observing AGN growth with HST and JWST:

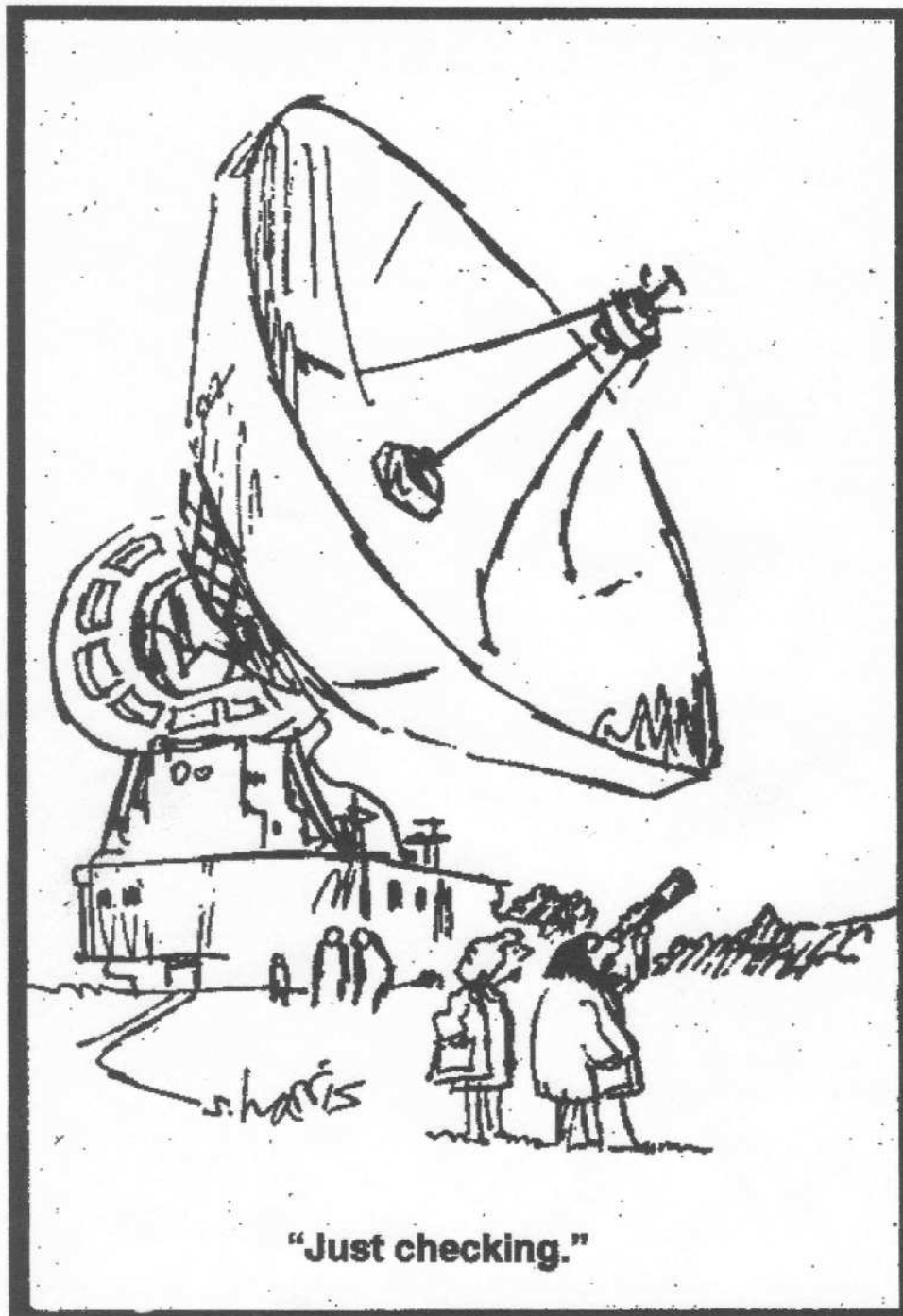
When during galaxy assembly did AGN growth take place?

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

*Collaborators: S. Cohen, R. Jansen (ASU), C. Conselice, S. Driver (UK), & H. Yan (OSU)
& (Ex) ASU Grad Students: N. Hathi, H. Kim, R. Ryan, M. Rutkowski, A. Straughn, & K. Tamura*



Colloquium at the University of Hawaii at Manoa, Honolulu, Hawaii, Wednesday November 10, 2010

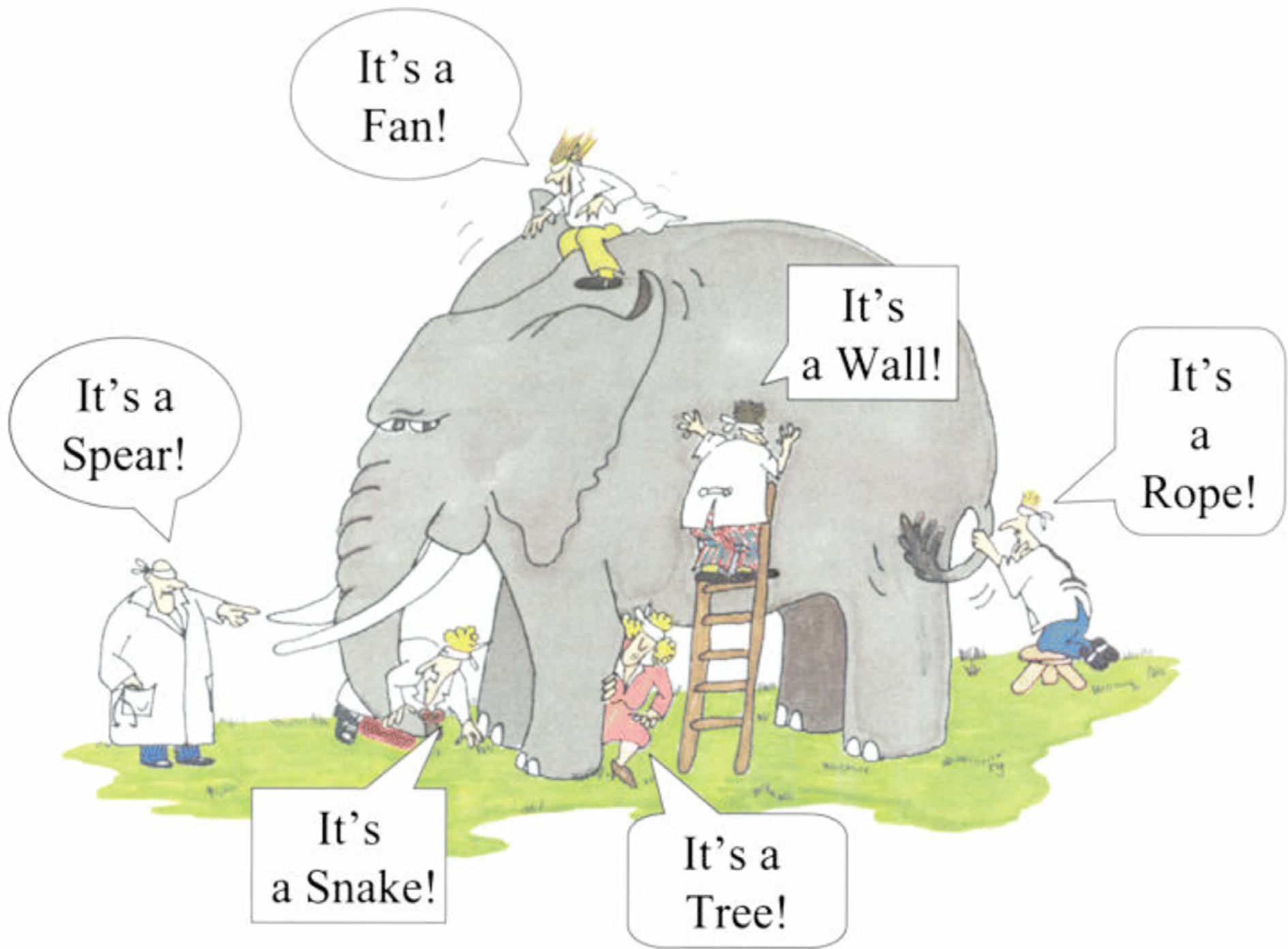


HST and JWST changed the career of this radio astronomer ...

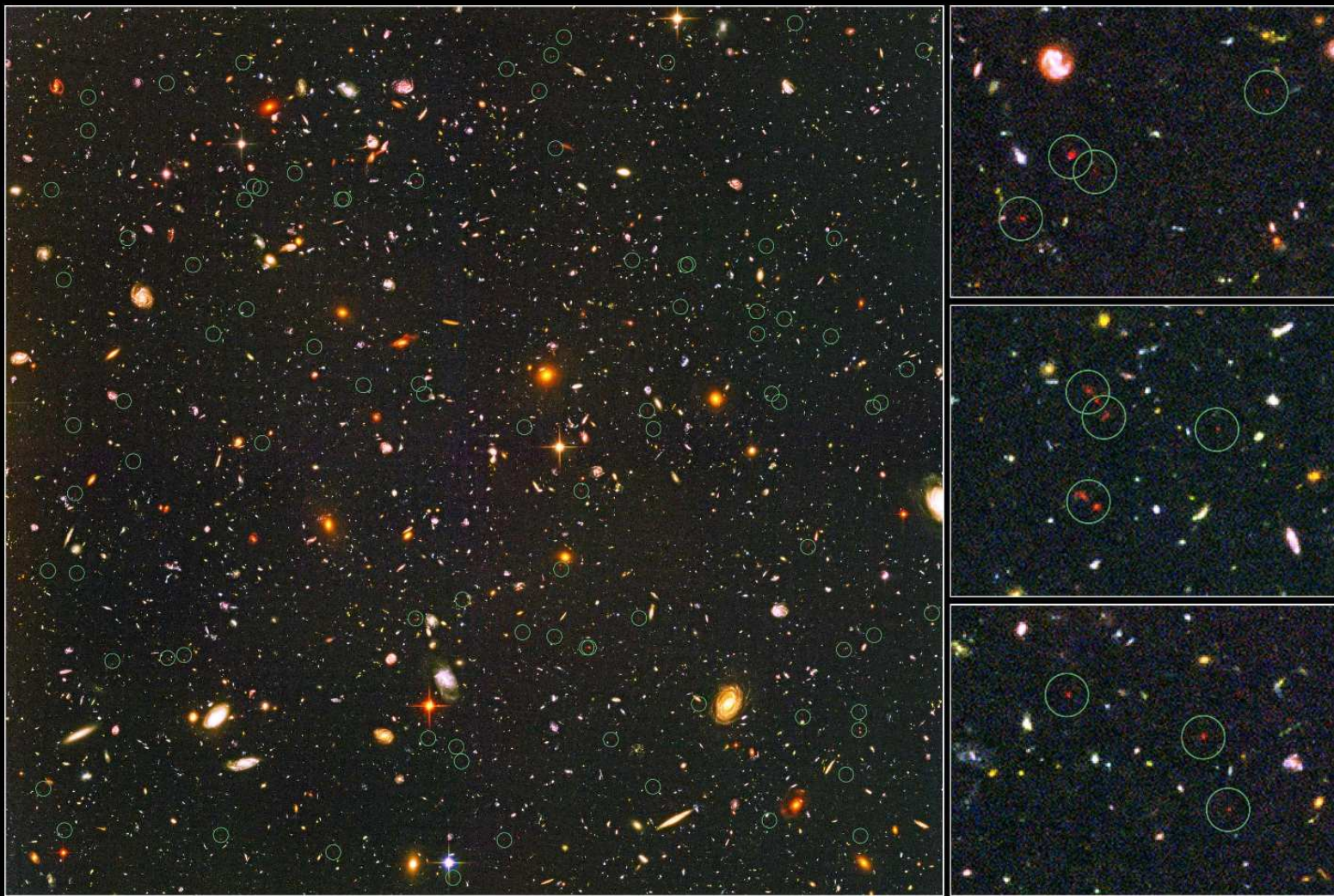
Outline

- (0) Summary of First Light and H-Reionization at $z \gtrsim 6$:
What has HST done, and what can JWST do?
- (1) HST/WFC3 & JWST: how did AGN/SMBH-growth go hand-in-hand with Galaxy Assembly?
- (2) (Major) mergers in GOODS & HUDF: Measuring Galaxy Assembly?
- (3) Variable Objects in the HUDF: A measure of AGN/SMBH-Growth?
- (4) Epoch dependent major merger rate to $AB \lesssim 27$ and Chandra $N(z)$.
- (5) SED ages of radio and X-ray host galaxies vs. epoch:
May trace AGN-growth vs. Galaxy Assembly directly.
- (6) Summary and Conclusions: $\Delta t(\text{X-ray}/\text{Radio X-ray field}) \lesssim 1 \text{ Gyr}$.

Sponsored by NASA/JWST. All charts ITAR cleared



AGN are the cosmic elephants that surprise both observers and theorists ... !



Distant Galaxies in the Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, R. Windhorst (Arizona State University) and H. Yan (Spitzer Science Center, Caltech)

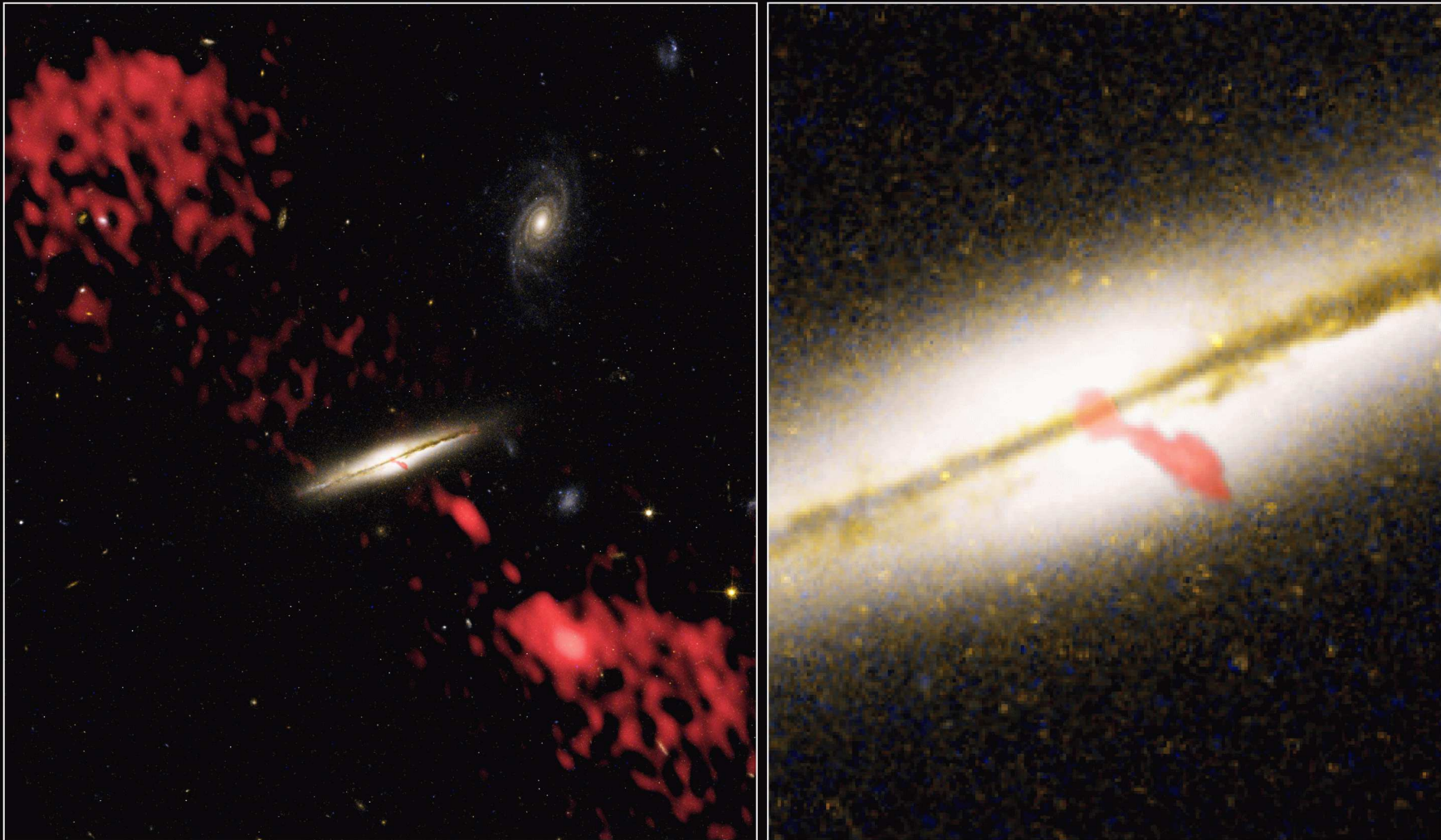
STScI-PRC04-28

In an HUDF³ volume at $z \simeq 2-6$:

$$M_{DM} \sim 10^{12-13} M_{\odot}, \quad M_{baryon} \sim 2 \times 10^{11-12} M_{\odot},$$

$$M_{grys}^* \sim 2 \times 10^{10-11} M_{\odot}, \quad M_{SMBH} \sim 4 \times 10^{7-8} M_{\odot}.$$

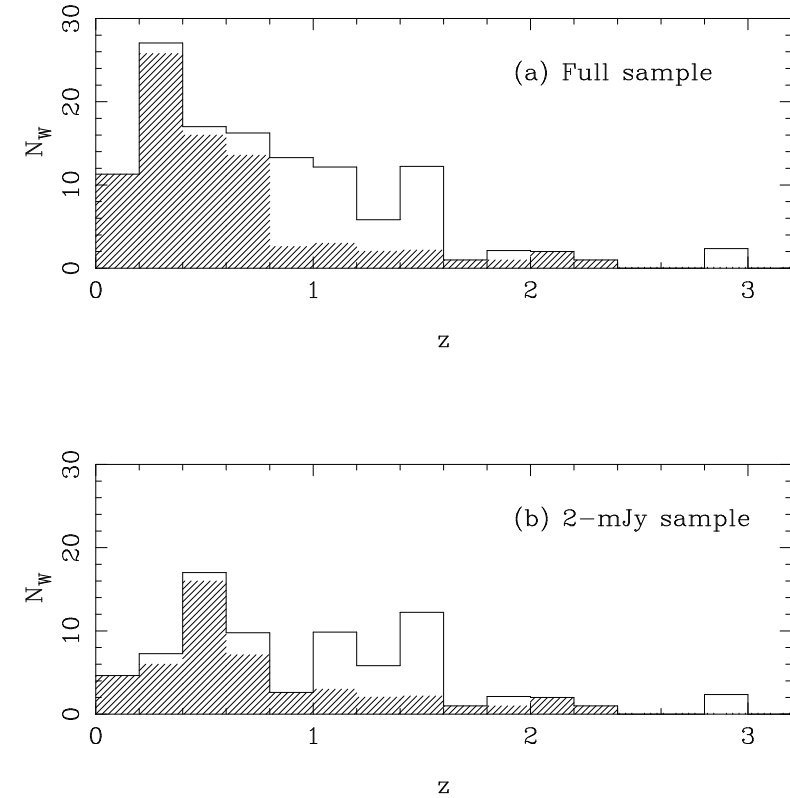
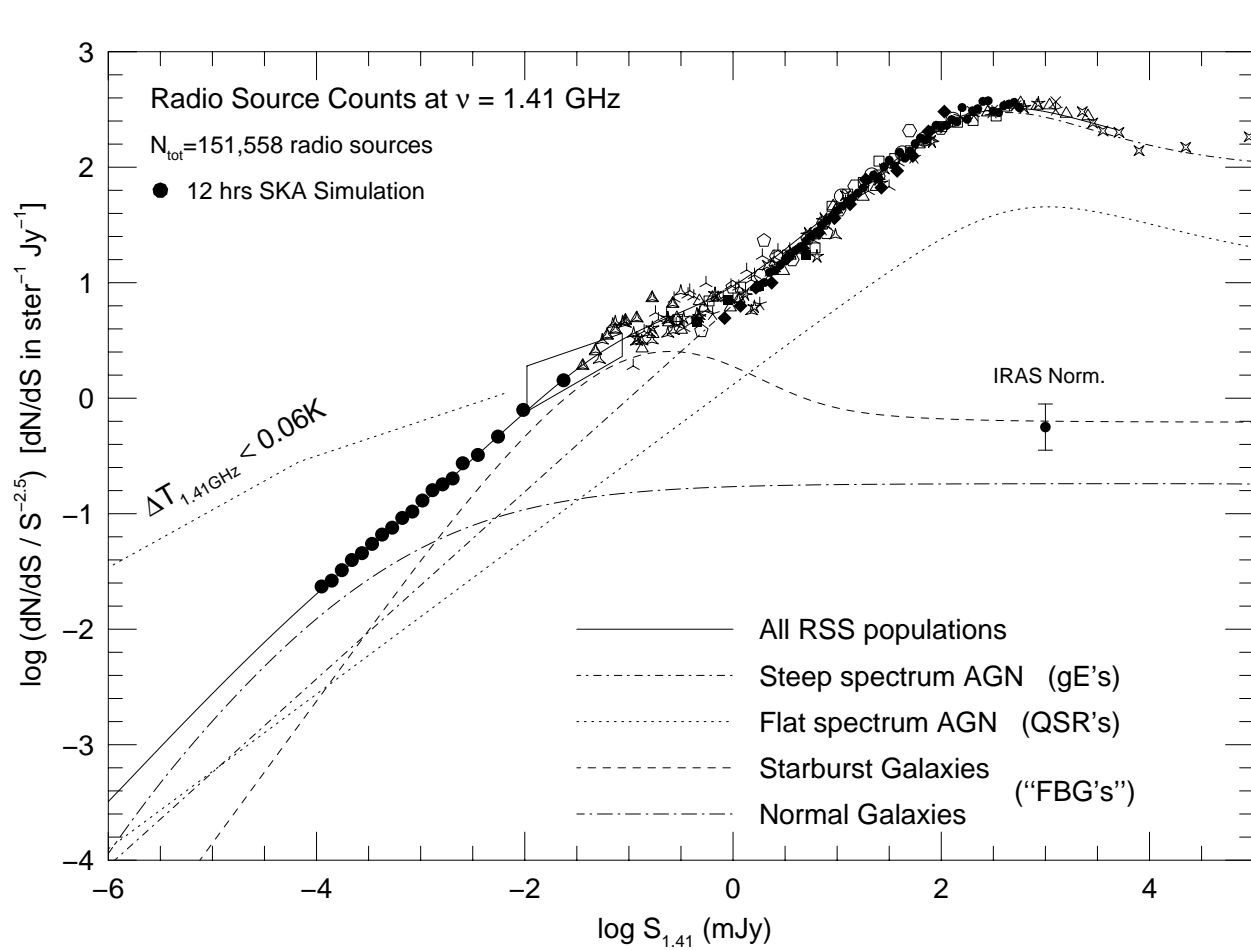
(0) How can HST & JWST measure Galaxy Assembly & SMBH/AGN Growth?



Radio Galaxy 0313-192
Hubble Space Telescope ACS WFC • Very Large Array

NASA, NRAO/AUI/NSF and W. Keel (University of Alabama) • STScI-PRC03-04

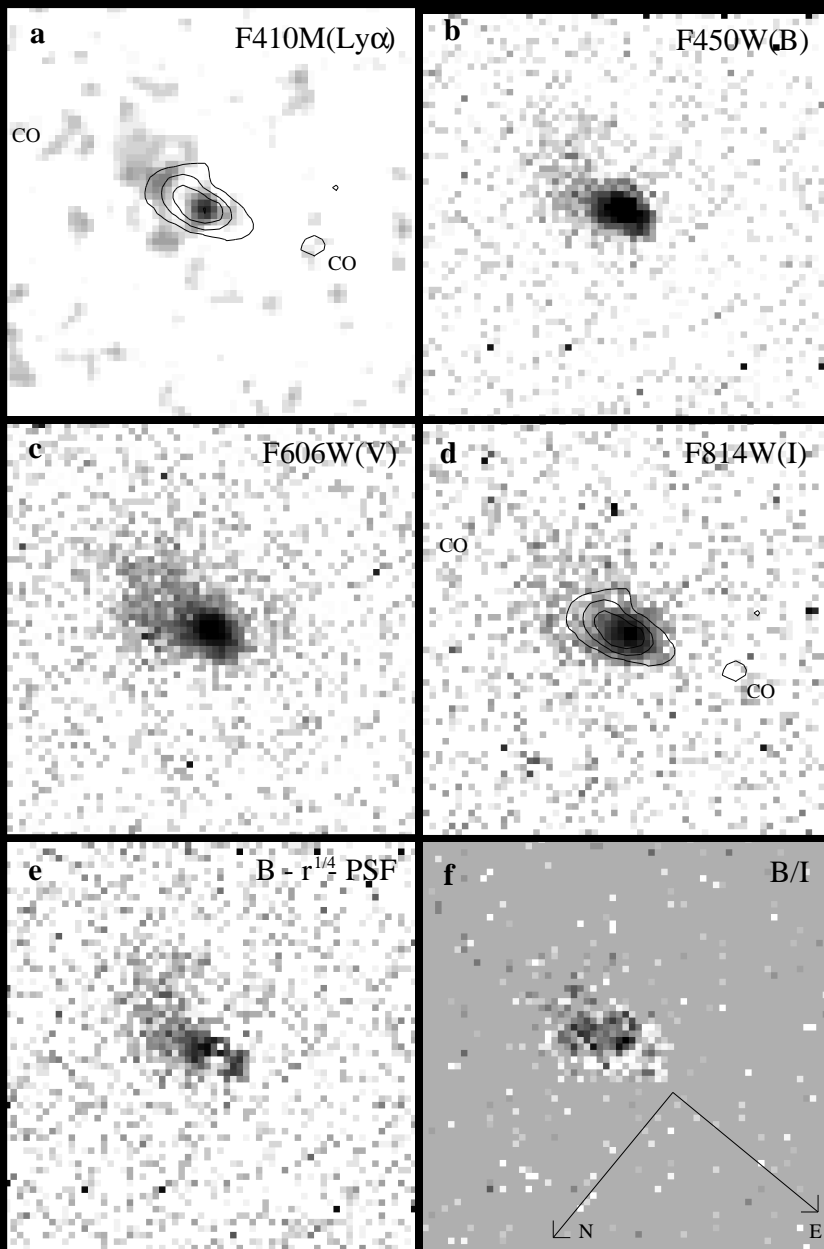
Question: How long after last (major) merger/SF does AGN activity show?



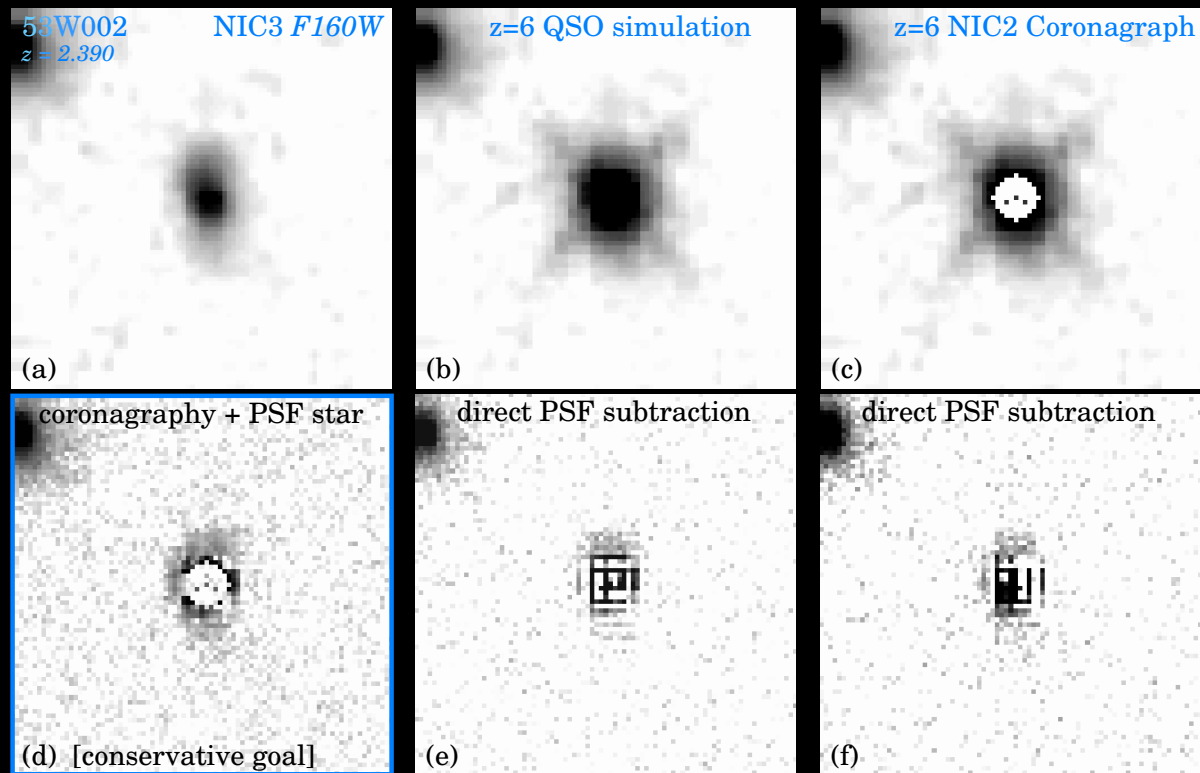
(LEFT) 1.41 GHz source counts (Windhorst et al. 1993, 2003; Hopkins et al. 2000) from 100 Jy to 100 nJy: AGN (monsters) dominate $\gtrsim 1$ mJy, starbursts below 1 mJy [12-hr SKA simulation below $10 \mu\text{Jy}$].

(RIGHT) Redshift distribution of mJy radio sources (Waddington⁺ 2001):

- Median redshift $z_{\text{med}} \lesssim 1$ at all flux levels, due to radio K-correction.
- Same in X-rays \implies Radio and X-ray fairly poor high-z AGN tracers!



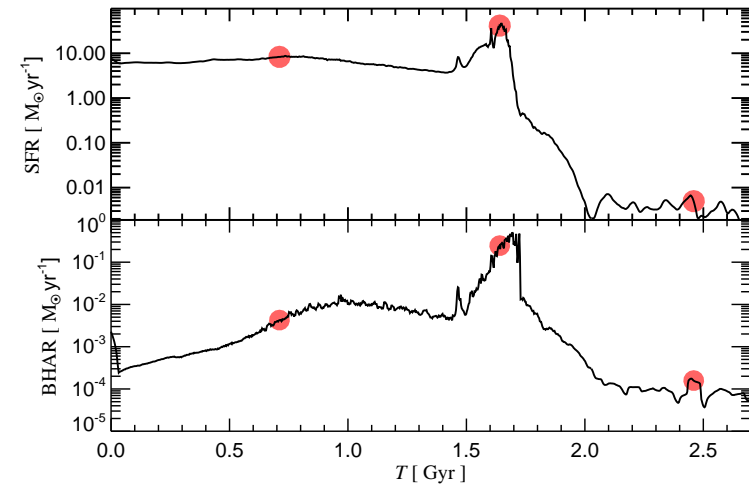
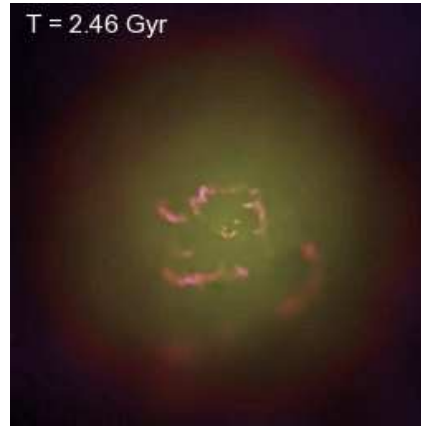
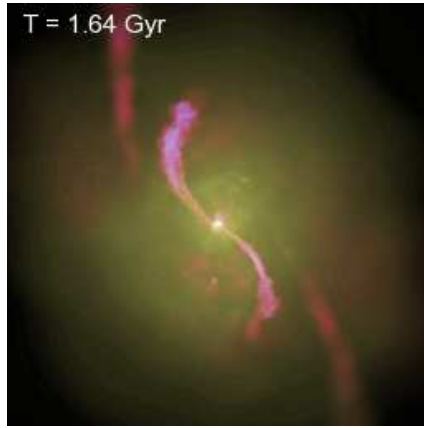
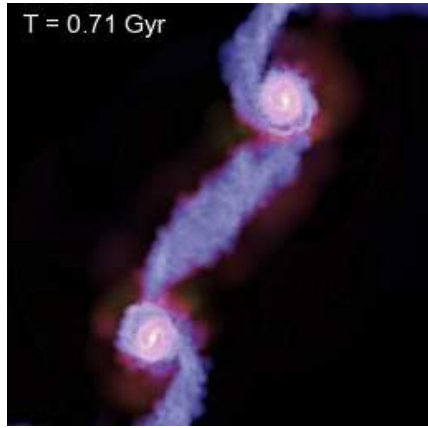
(Left): HST/PC of radio galaxy 53W002 at $z=2.39$ (Windhorst et al. 1998): rest-UV $r^{1/4}$ -law + Ly α & Cont AGN-cloud.



Coronagraph simulation of $z=6$ SDSS QSO host (using HST/NIC2+Corona). Can measure $>L^*$ AGN-host at $z \gtrsim 6$.

- JWST can measure AGN hosts 3 mag fainter in restframe UV-Opt to $z \lesssim 20$.
- Such AGN are very rare. JWST must use other ways to trace AGN-growth.

(0) How to trace SMBH/AGN-growth after Galaxy Merger &/or Starburst?

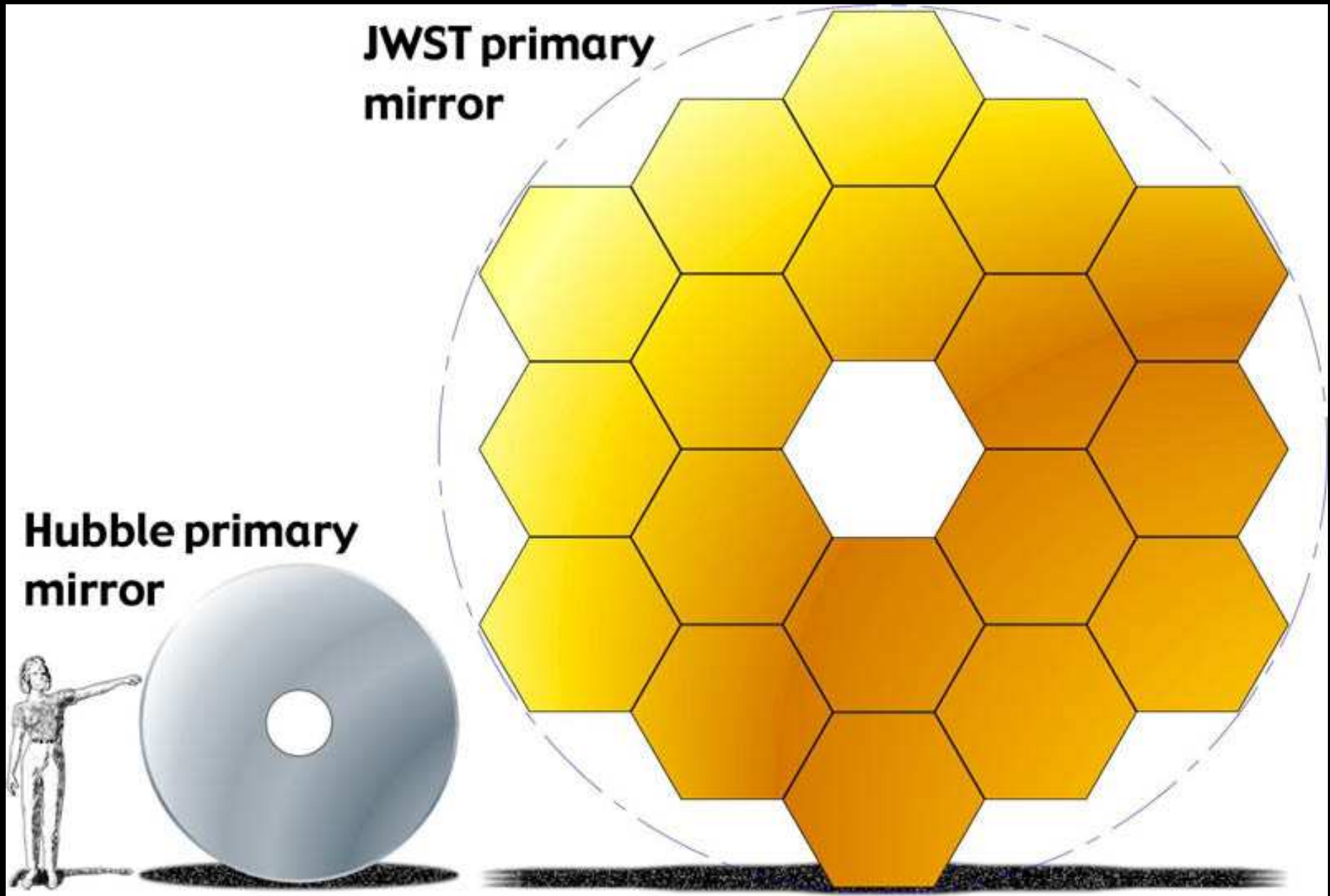


- [LEFT] Simulated merger of two disk galaxies at three different times, including the effects of SMBH growth and AGN feedback by Springel, di Matteo, Hernquist (2005, ApJ, 620, 79). Shown is the gas distribution with color indicating temperature, and brightness indicating gas density.

- [RIGHT] Evolution of the accretion rate onto the SMBH (top) and the SF-rate (bottom). Red dots mark the times of the three images.

⇔ In hydrodynamical simulations, the object resembles a tadpole galaxy ~ 0.7 Gyr after the merger starts, the AGN is triggered and expels the dust $\gtrsim 1.6$ Gyr after the merger starts, *i.e.*, $\gtrsim 1$ Gyr after the starburst stage.

(1) JWST: First Light, Reionization, Galaxy Assembly & AGN growth



JWST $\sim 2.5\times$ larger than Hubble, so at $\sim 2.5\times$ larger wavelengths:
JWST has the same resolution in the near-IR as HST in the optical.

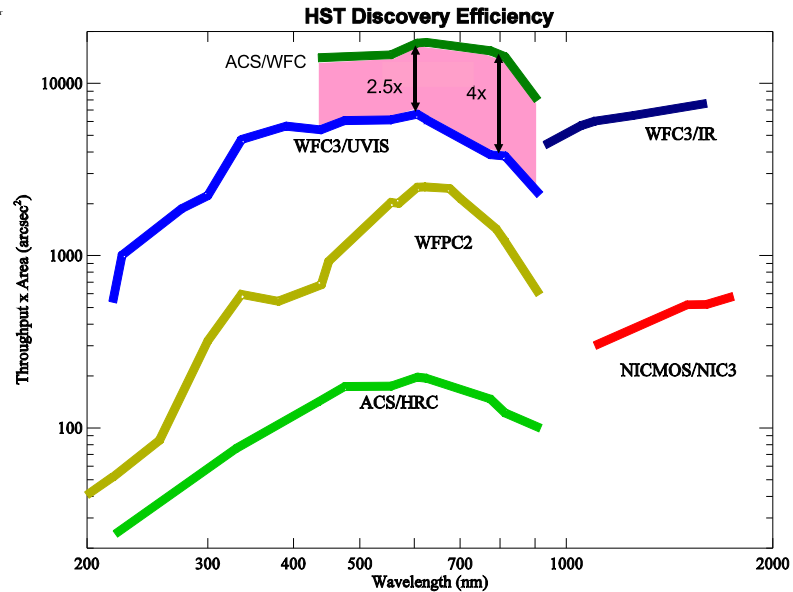


WFC3: Hubble's new Panchromatic High-Throughput Camera



Hubble Space Telescope Program

Role of ACS in HST Post-SM4 Imaging Capability



ACS/WFC superior to WFC3 survey efficiency at visible-red wavelengths

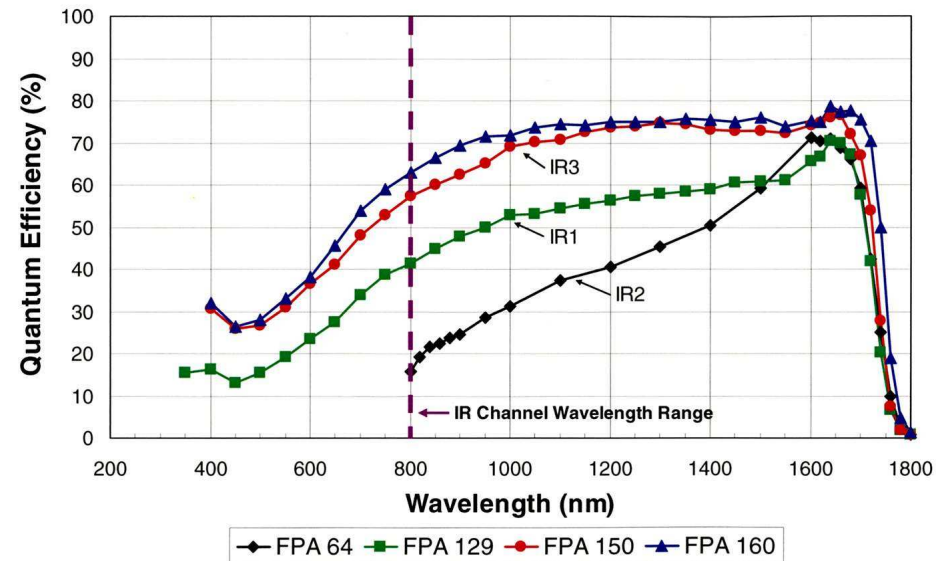
030507_PML_ACS_Status.ppt

9



Hubble Space Telescope Program

FPA 160 QE



May 2, 2007

Wide Field Camera 3 Monthly Status Review

061107_PML_STIC.ppt

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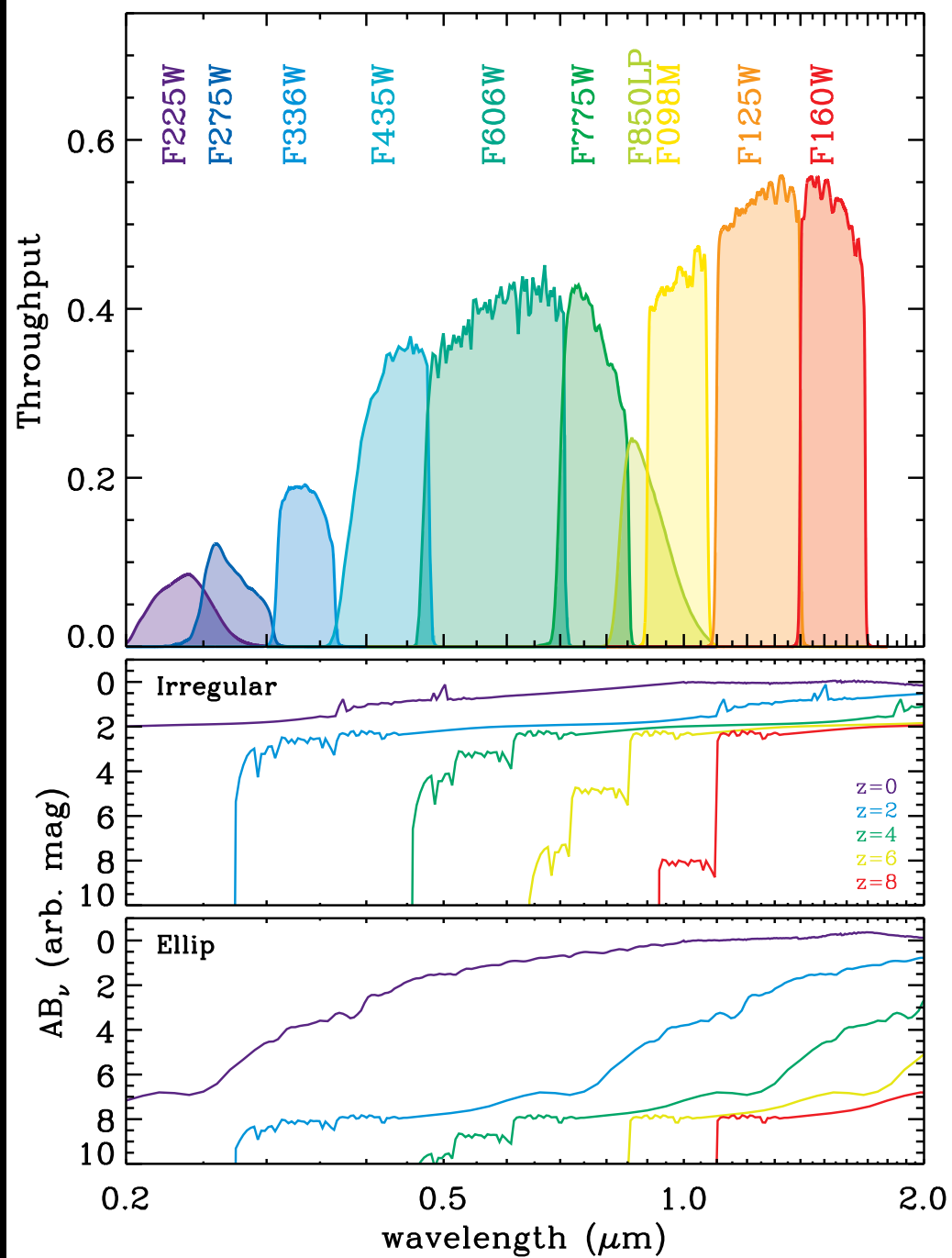
WFC3/UVIS channel has unprecedented UV–blue throughput & areal coverage:

- $QE \gtrsim 70\%$, $4k \times 4k$ E2V array of $0''.04$ pixel, $FOV \simeq 2'.67 \times 2'.67$

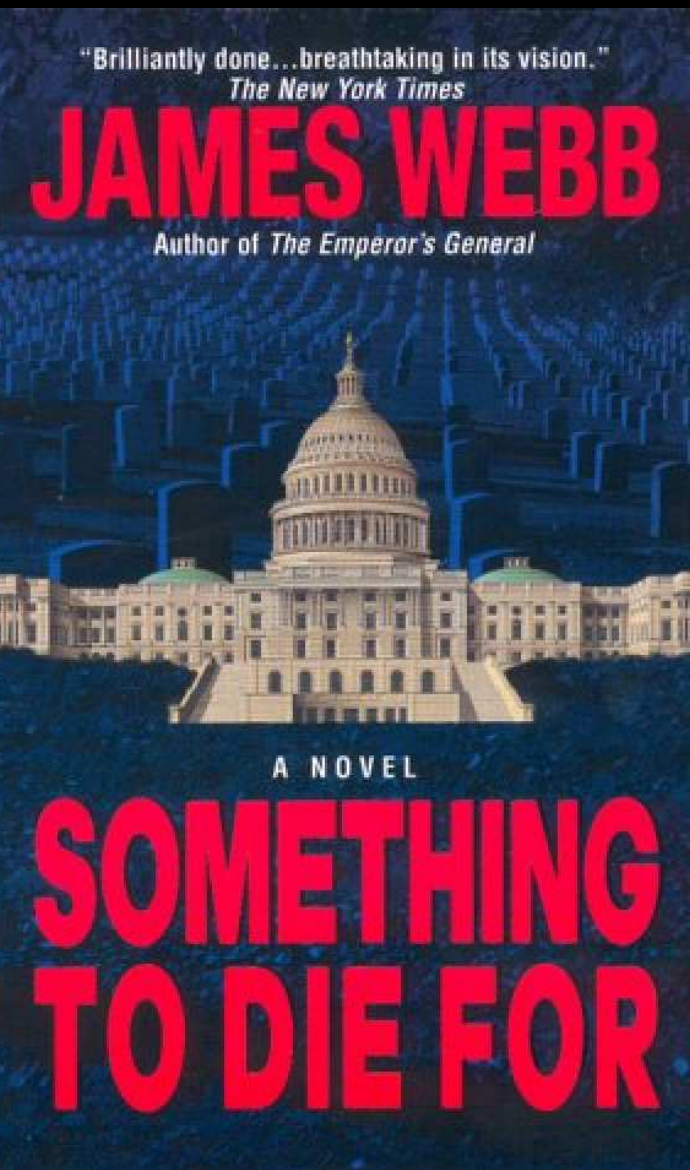
WFC3/IR channel has unprecedented near-IR throughput & areal coverage:

- $QE \gtrsim 70\%$, $1k \times 1k$ Hawaii array of $0''.13$ pixel, $FOV \simeq 2'.25 \times 2'.25$

⇒ WFC3 opened major new parameter space for astrophysics in 2009.



Panchromatic HST/WFC3 & ACS filters used in GOODS-South ERS.
Filters designed for Star-formation and galaxy mass assembly at $z \simeq 1-5$.



Need hard-working grad students & postdocs in ≥ 2014 ... It'll be worth it!

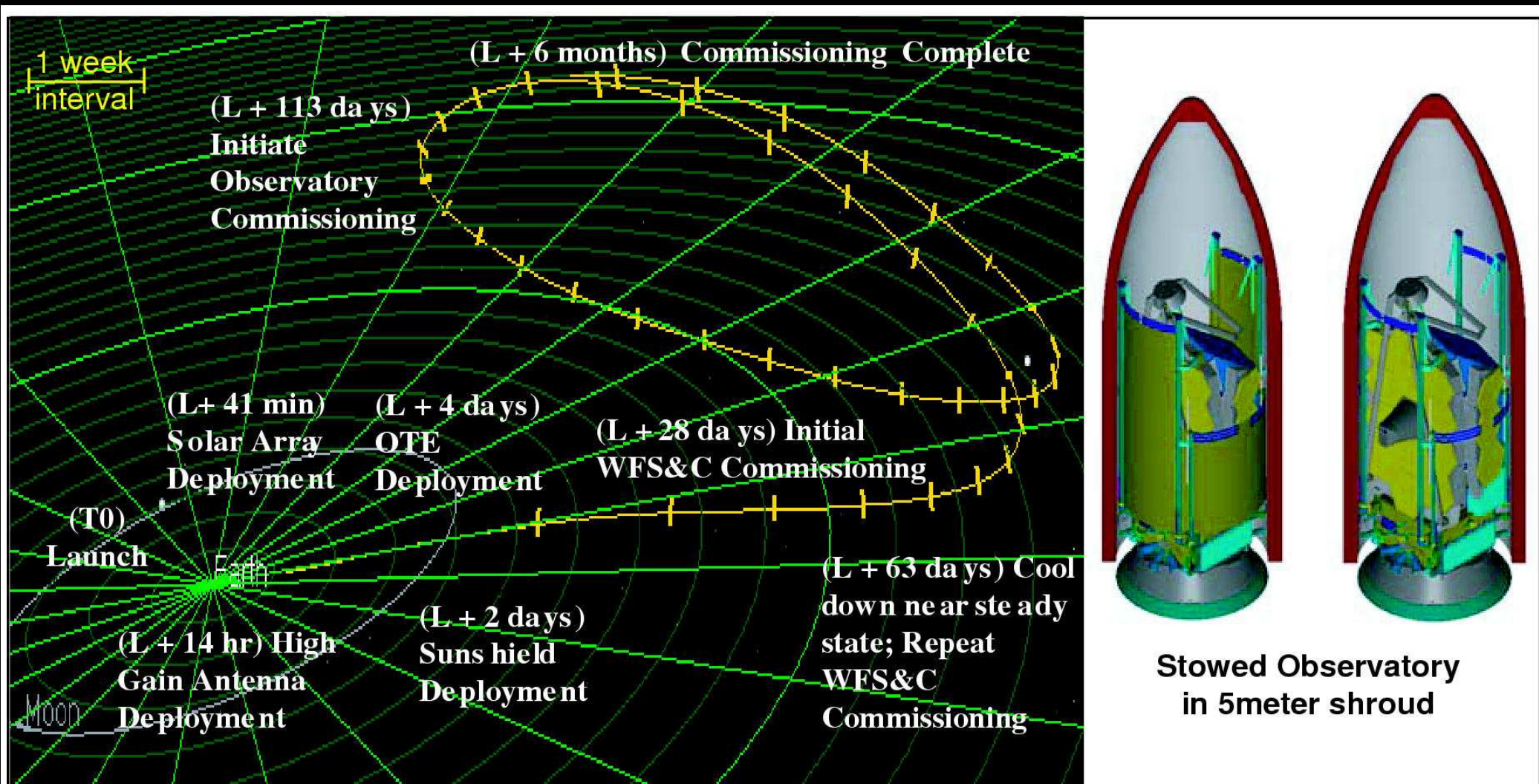
(RIGHT) Life-size JWST prototype on the Capitol Mall, May 2007 ...

- (1a) What is the James Webb Space Telescope (JWST)?



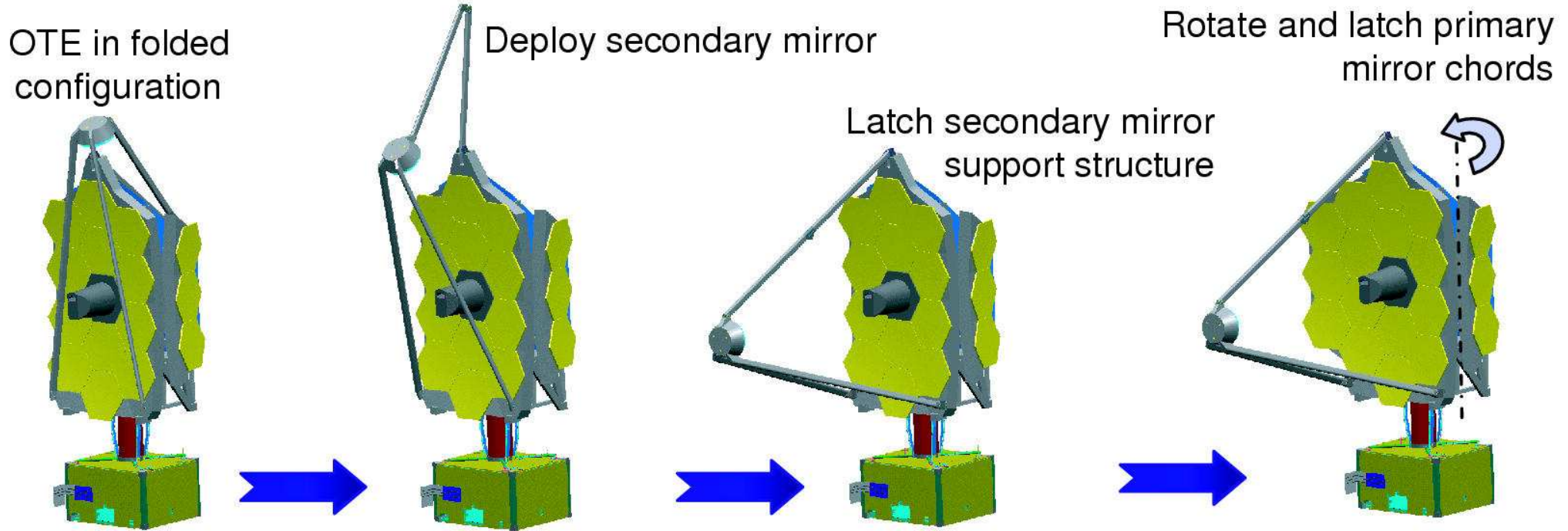
- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy from 0.7 to $29 \mu\text{m}$, to be launched in June $\gtrsim 2014$.
- Nested array of sun-shields to keep its ambient temperature at $35\text{-}45 \text{ K}$, allowing faint imaging ($AB \lesssim 31.5$) and spectroscopy ($AB \lesssim 29 \text{ mag}$).

- (1a) How will JWST travel to its L2 orbit?

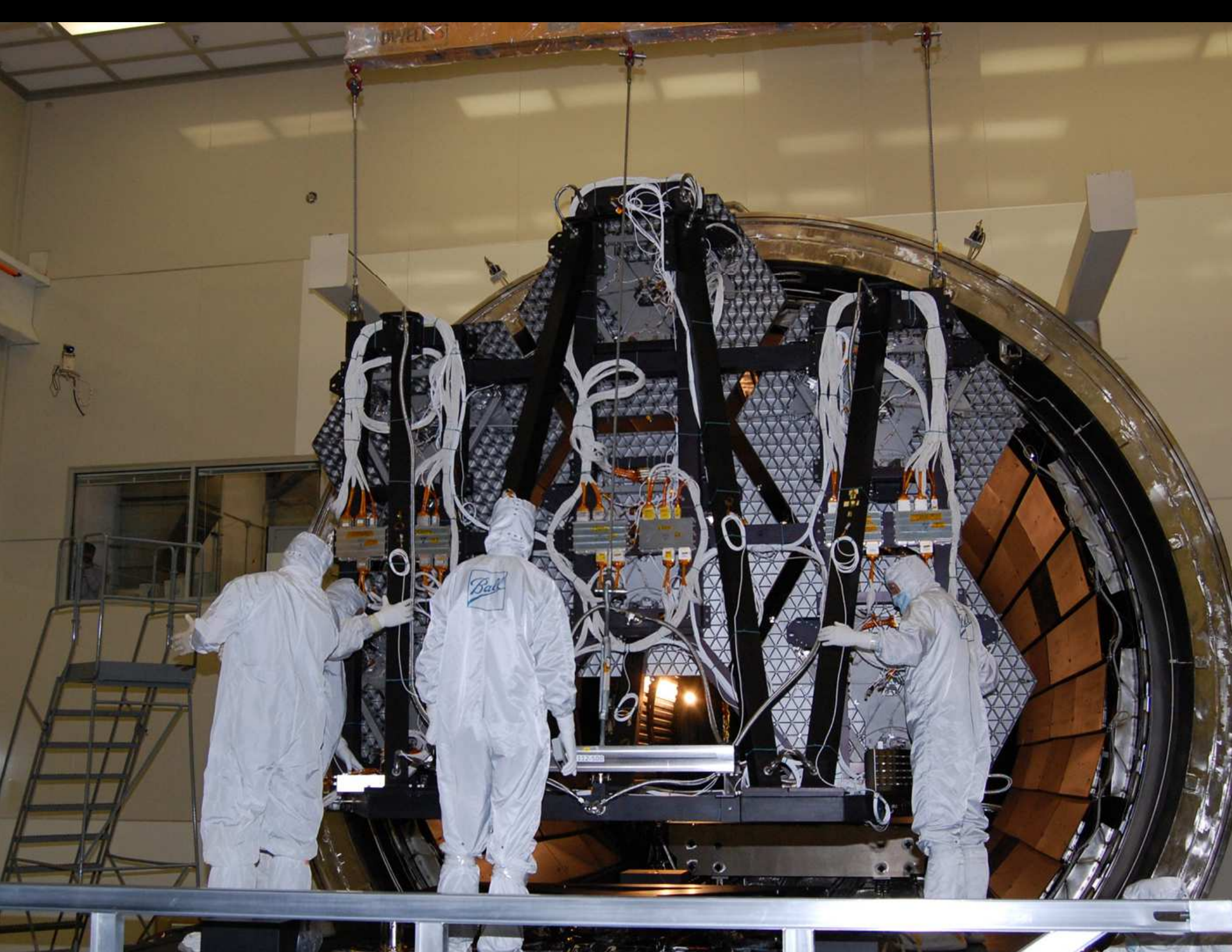


- After launch in June 2014 with an Ariane-V, JWST will orbit around the the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim 70\%$ of the time, and send data back to Earth every day.

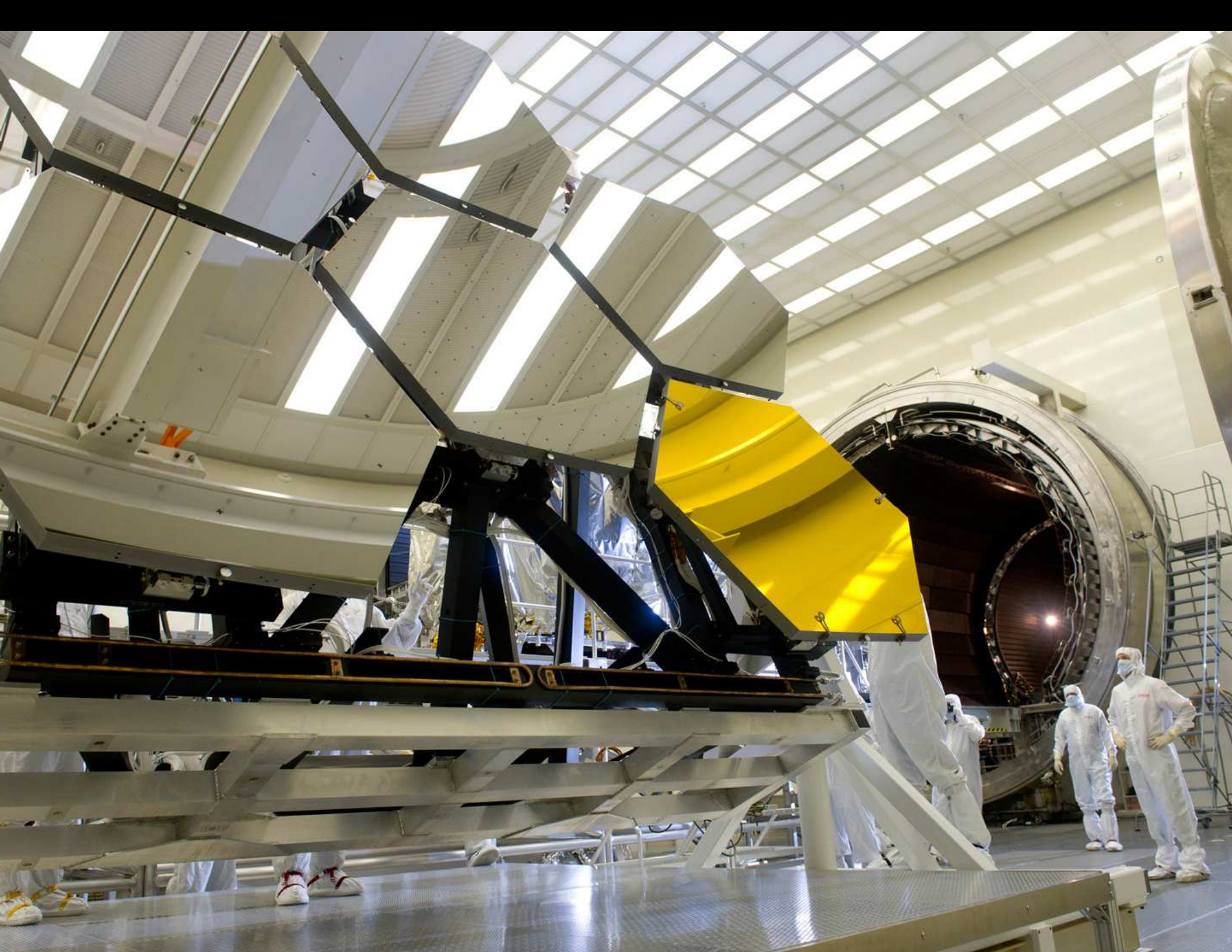
- (1a) How will JWST be automatically deployed?

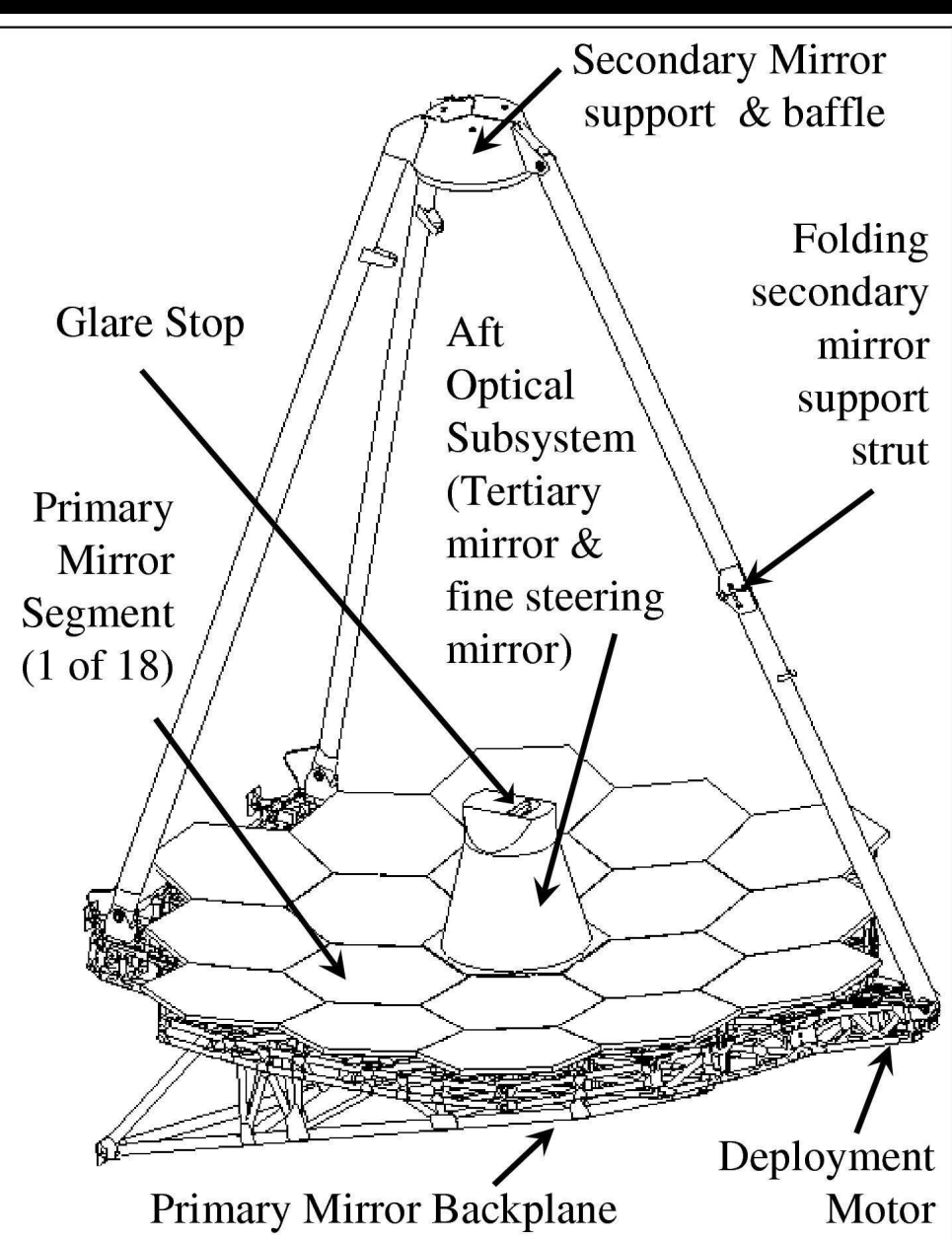


- During its several month journey to L2, JWST will be automatically deployed in phases, its instruments will be tested and calibrated, and it will then be inserted into an L2 halo orbit, 1.5 million km from Earth.
- The entire JWST deployment sequence will be tested several times on the ground — but only in 1-G: component and system tests at JSC.
- Component fabrication, testing, & integration is on schedule: 3 out of 18 flight mirrors completely done, and at the 45K $2.0\mu\text{m}$ diffraction limit!







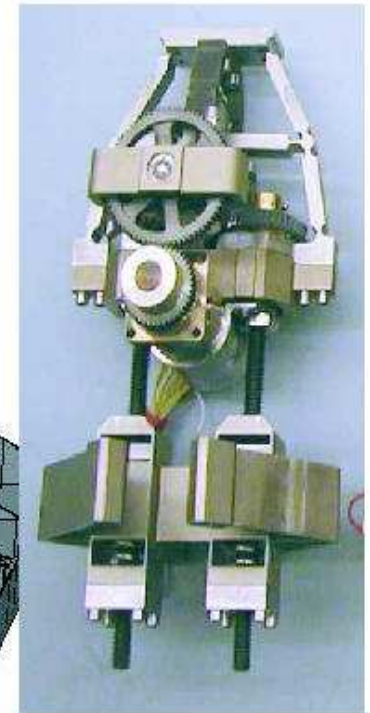
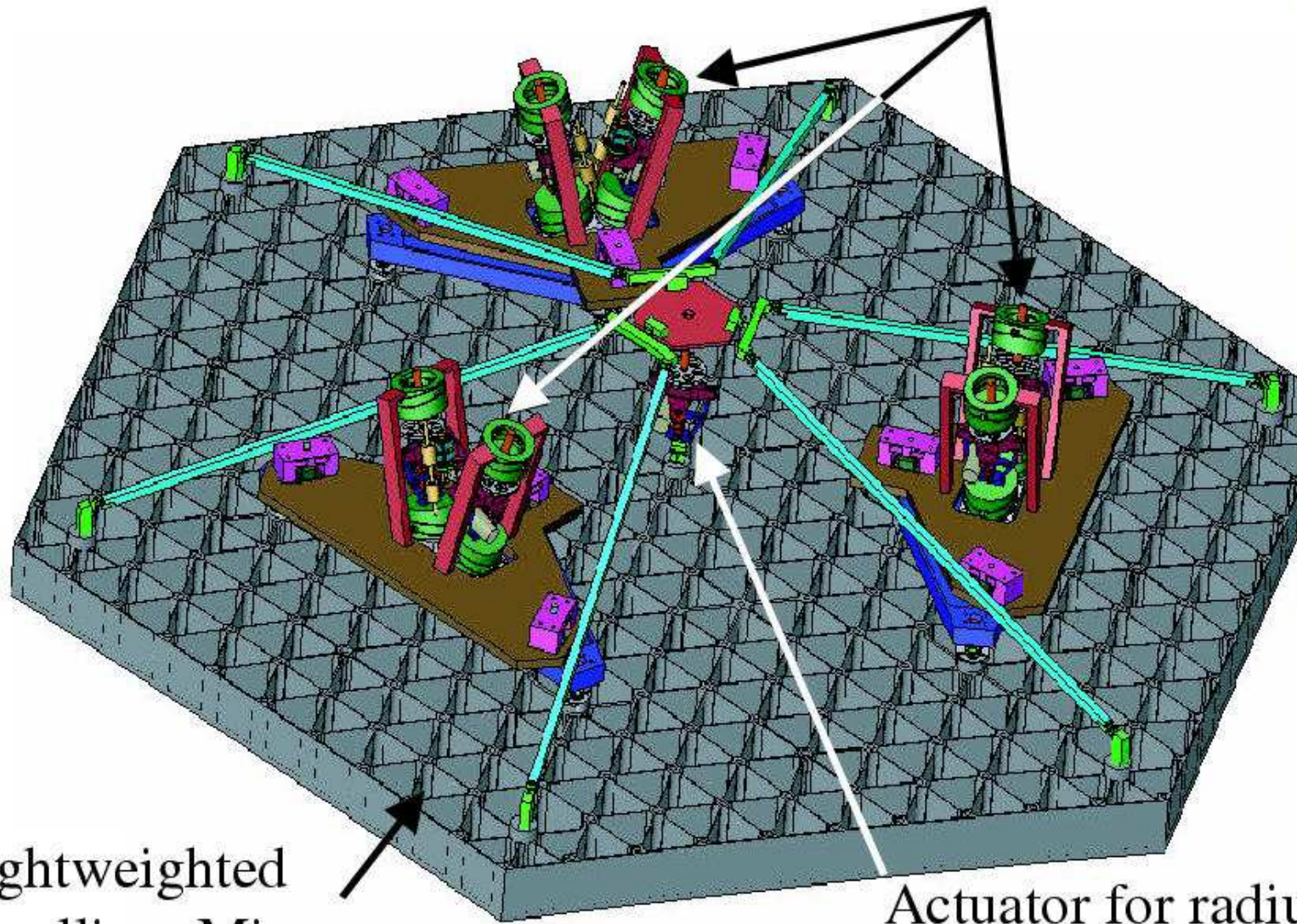


Ball 1/6-model for WFS: diffraction-limited $2.0 \mu\text{m}$ images ($\text{Strehl} \gtrsim 0.85$).

Wave-Front Sensing tested hands-off at 45 K in 1-G at JSC in 2011-2013.

In L2, WFS updates every 10 days depending on scheduling/SC-illumination.

Actuators for 6 degrees of freedom rigid body motion

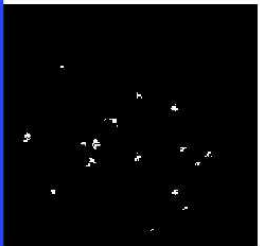
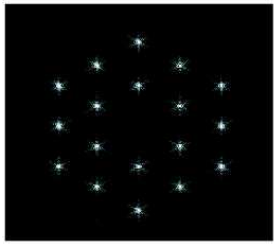
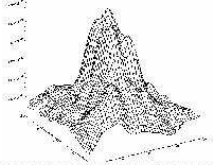





Actuator development unit

Lightweighted Beryllium Mirror

Actuator for radius of curvature adjustment

Active mirror segment support through hexapods (7 d.o.f.), similar to Keck.
Redundant & doubly-redundant mechanisms, quite forgiving against failures.

<i>First light NIRC<i>am</i></i>			Initial Capture	Final Condition
	1. Segment Image Capture		18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 μm, < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
2. Coarse Alignment Secondary mirror aligned Primary RoC adjusted			Primary Mirror segments: < 1 mm, < 10 arcsec tilt Secondary Mirror : < 3 mm, < 5 arcmin tilt	WFE < 200 μm (rms)
3. Coarse Phasing - Fine Guiding (PMSA piston)			WFE: < 250 μm rms	WFE < 1 μm (rms)
4. Fine Phasing			WFE: < 5 μm (rms)	WFE < 110 nm (rms)
5. Image-Based Wavefront Monitoring			WFE: < 150 nm (rms)	WFE < 110 nm (rms)

JWST's Wave Front Sensing and Control is similar to that at Keck and HET.
 Successful WFS demo of H/W, S/W on 1/6 scale model ($2\ \mu\text{m}$ -Strehl $\gtrsim 0.85$).
 Need WFS-updates every ~ 10 days, depending on scheduling/SC-illumination.

- (1b) What instruments will JWST have? US (UofA, JPL), ESA, and CSA.



Instrument Overview

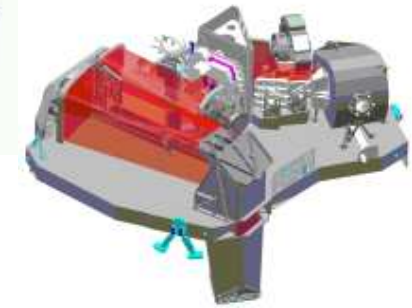
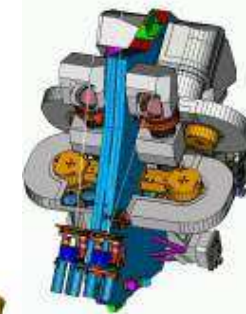
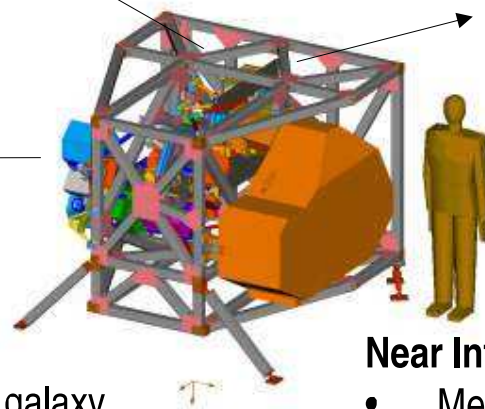
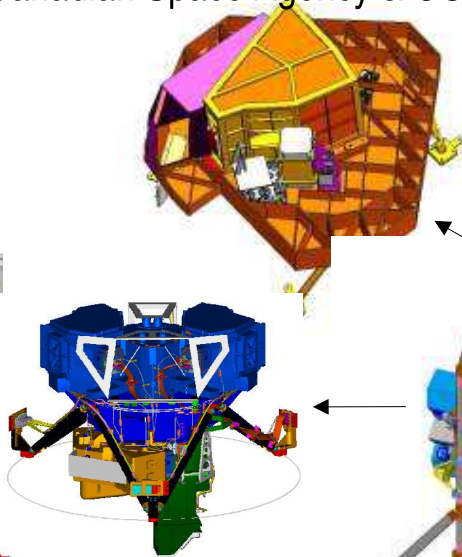


Fine Guidance Sensor (FGS)

- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

Near Infra-Red Camera (NIRCam)

- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC



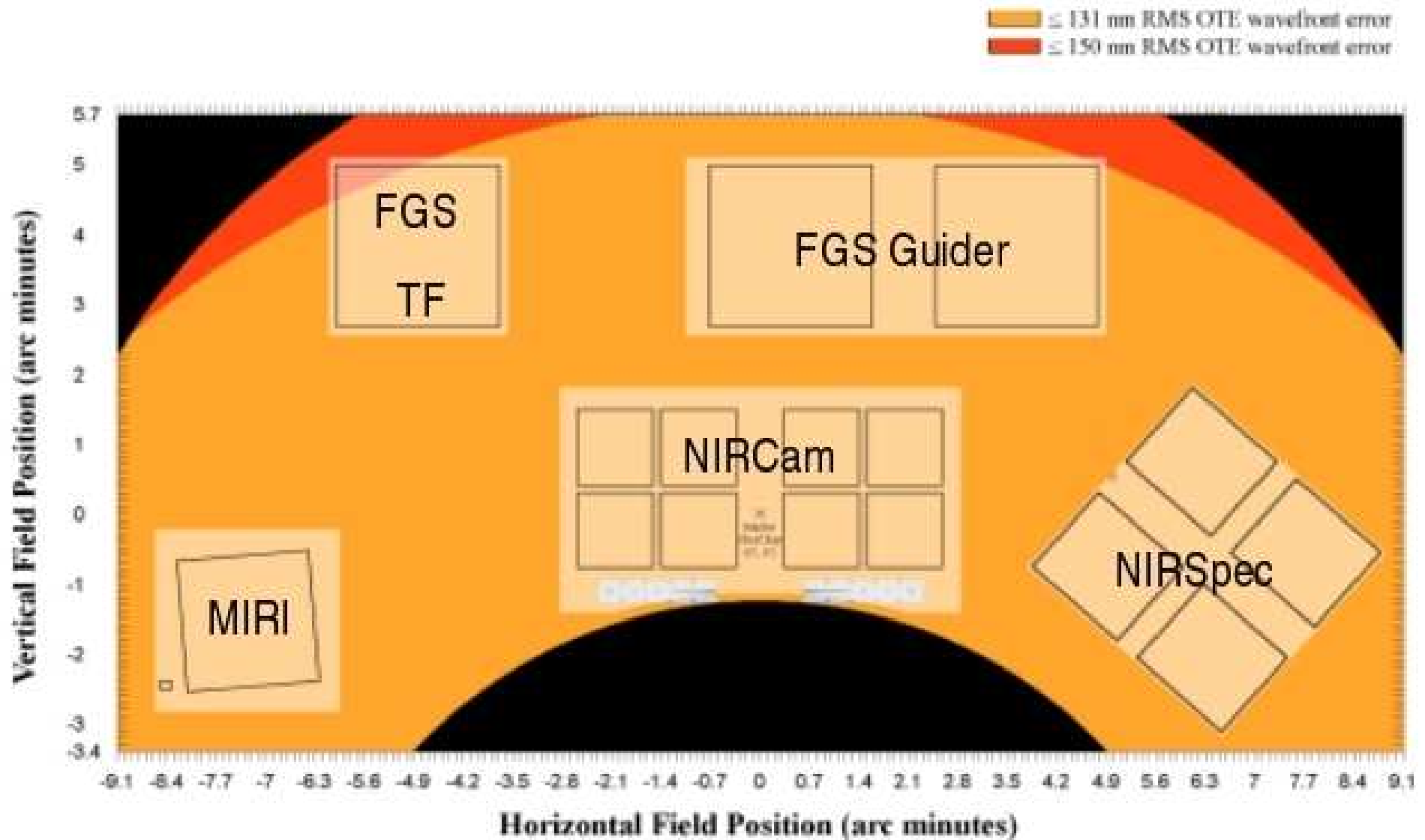
Mid-Infra-Red Instrument (MIRI)

- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

Near Infra-Red Spectrograph (NIRSpec)

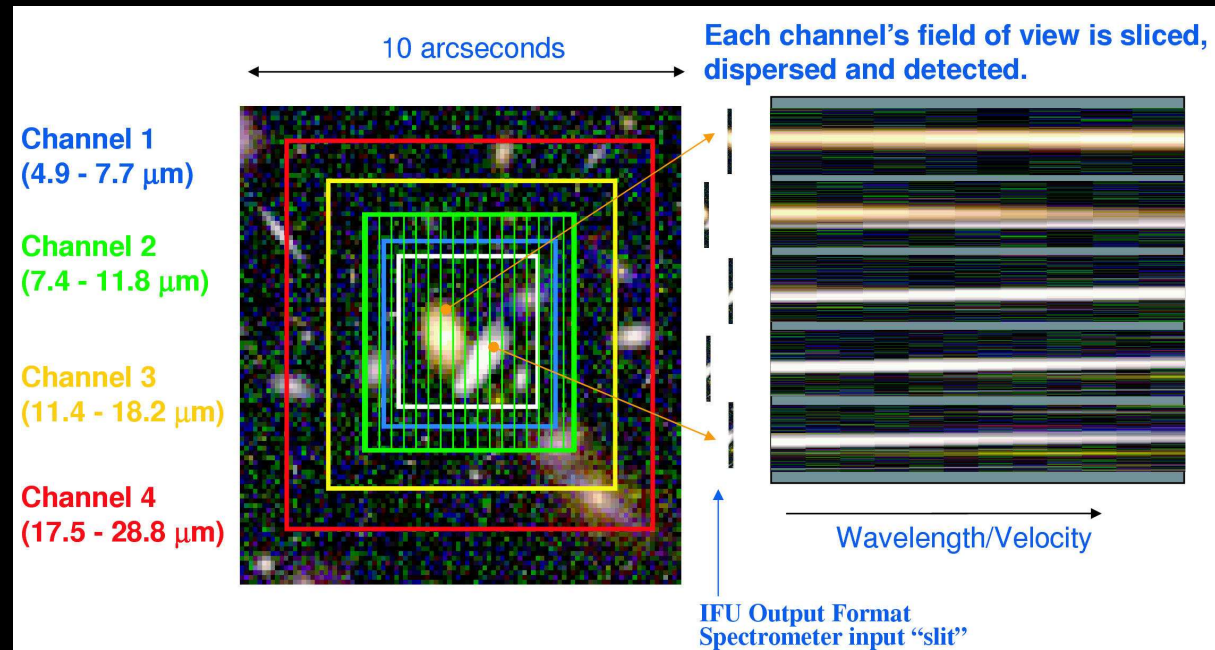
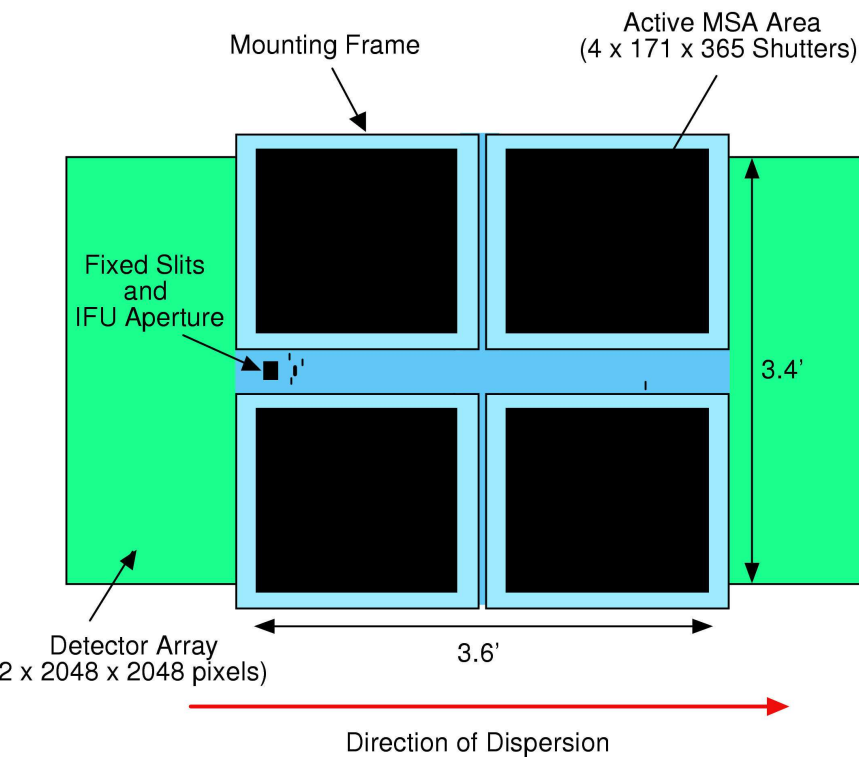
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

- (1b) What instruments will JWST have?



All JWST instruments can in principle be used in parallel observing mode:

- Currently only being implemented for parallel *calibrations*.



JWST offers significant multiplexing for faint object spectroscopy:

- NIRSPEC/MSA with $4 \times 62,415$ independently operable micro-shutters (MEMS) that cover $\lambda \simeq 1\text{--}5 \mu\text{m}$ at $R \simeq 100\text{--}1000$.
- MIRI/IFU with 400 spatial pixels covering $5\text{--}29 \mu\text{m}$ at $R \sim 2000\text{--}4000$.
- FGS/TFI that covers a $2'2 \times 2'2$ FOV at $\lambda \simeq 1.6\text{--}4.9 \mu\text{m}$ at $R \simeq 100$.
- [● NIRCAM offers $R \simeq 5$ imaging from $0.7\text{--}5 \mu\text{m}$ over two $2'3 \times 4'6$ FOV's.]



Despite NASA's CAN-do approach: Must find all the cans-of-worms ...

Northrop Grumman Expertise in Space Deployable Systems

- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements





Baseline "Cup Down" Tower Configuration at JSC (Before)

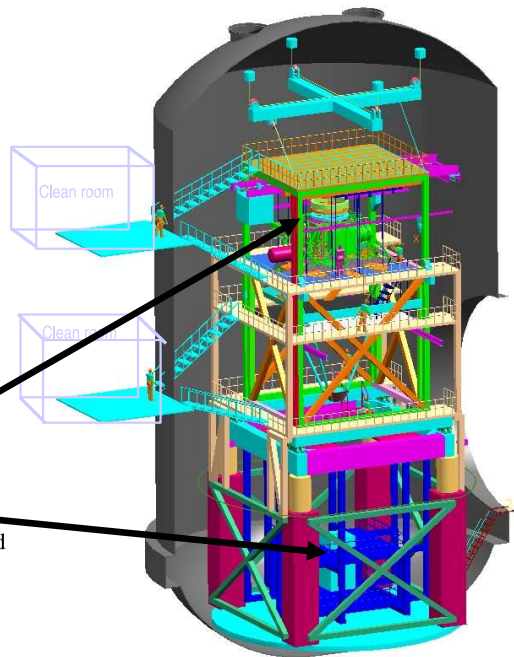
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

Current plan calls for 33KW cooldown capability, 12 KW steady state, 300-500mW N2 cooling

JSC currently has 7 KW He capability

Current plan includes 10 trucks of LN2/day during cooldown

Interferometers, Sources, Null Lens and Alignment Equipment Are in Upper and Lower Pressure Tight Enclosure Inside of Shroud



JSC "Cup Up" Test Configuration (New Proposal)



No Metrology Tower and Associated Cooling H/W.

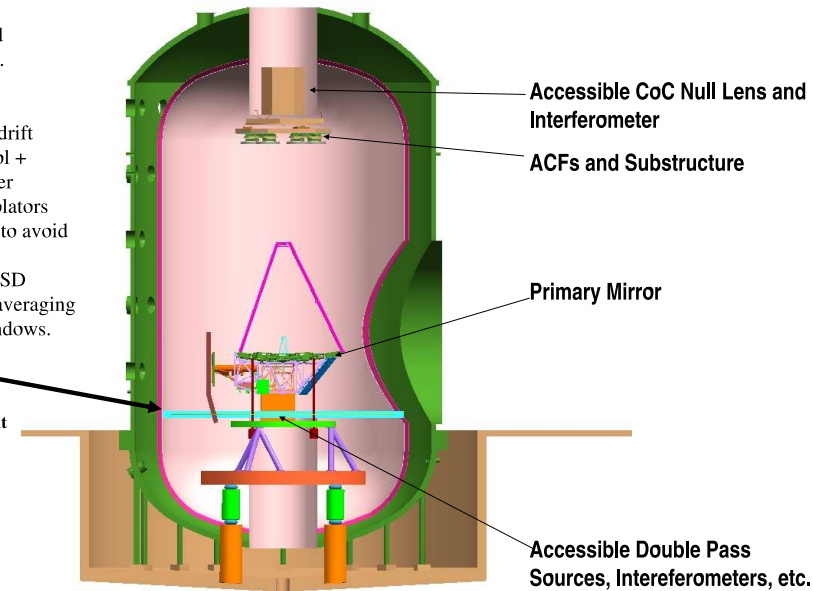
External Metrology

Two basic test options:

1. Use isolators, remove drift through fast active control + freeze test equipment jitter
2. Eliminate vibration isolators (but use soft dampeners) to avoid drift, freeze out jitter

Builds on successful AMSD heritage of freezing and averaging jitter, testing through windows.

Possible payload "floor" to separate ambient pressure and temperature.



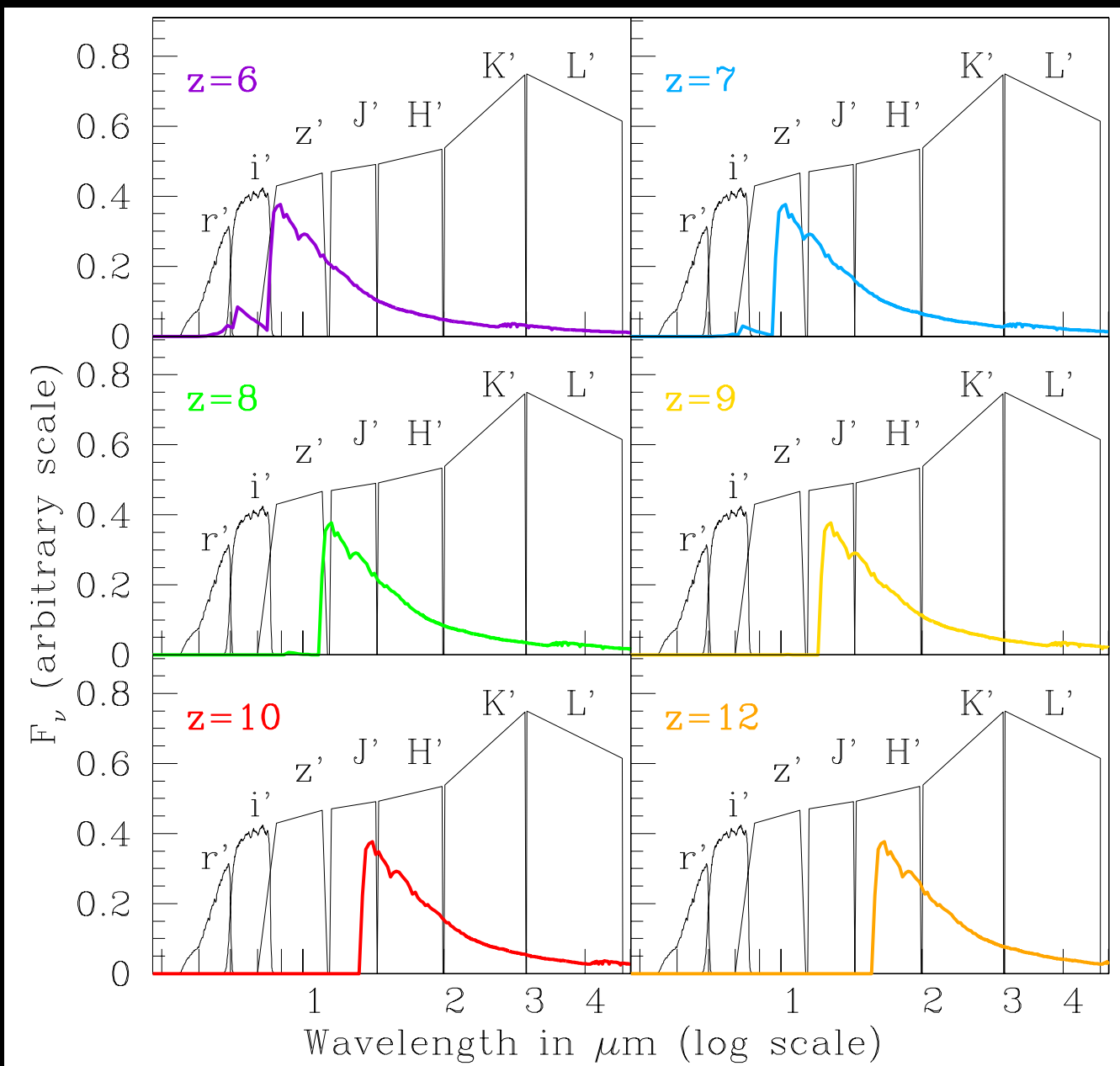
Drawing care of ITT

Page 6

JWST underwent several significant replans and risk-reduction schemes:

- $\lesssim 2003$: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6), *i.e.*, demonstration in a relevant environment — ground or space.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010: Passes Mission Critical Design Review. Revisit testing procedures.

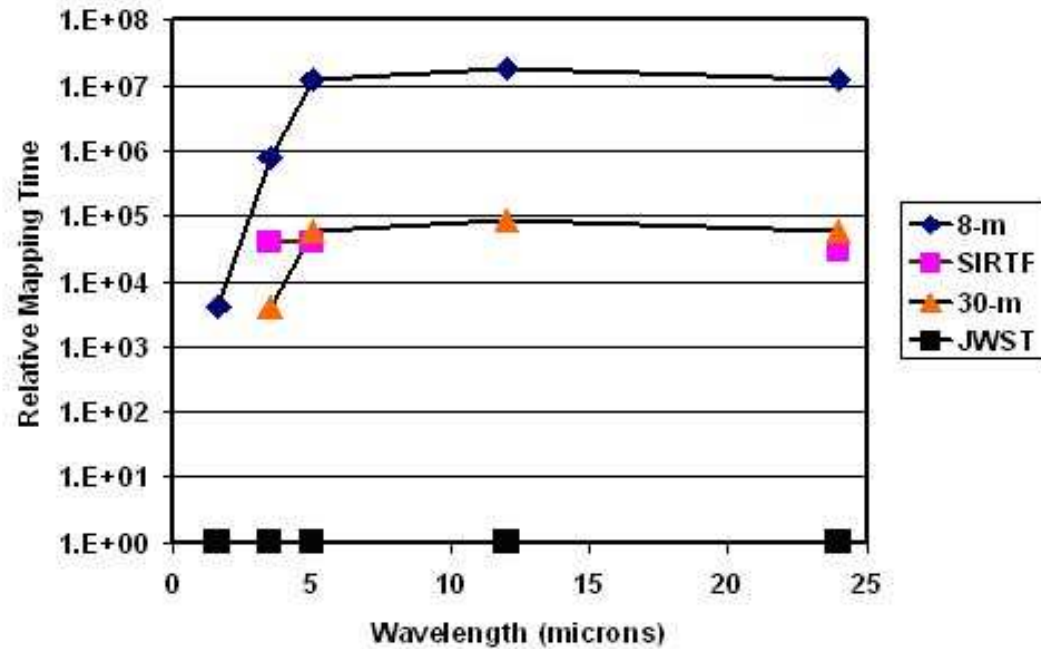
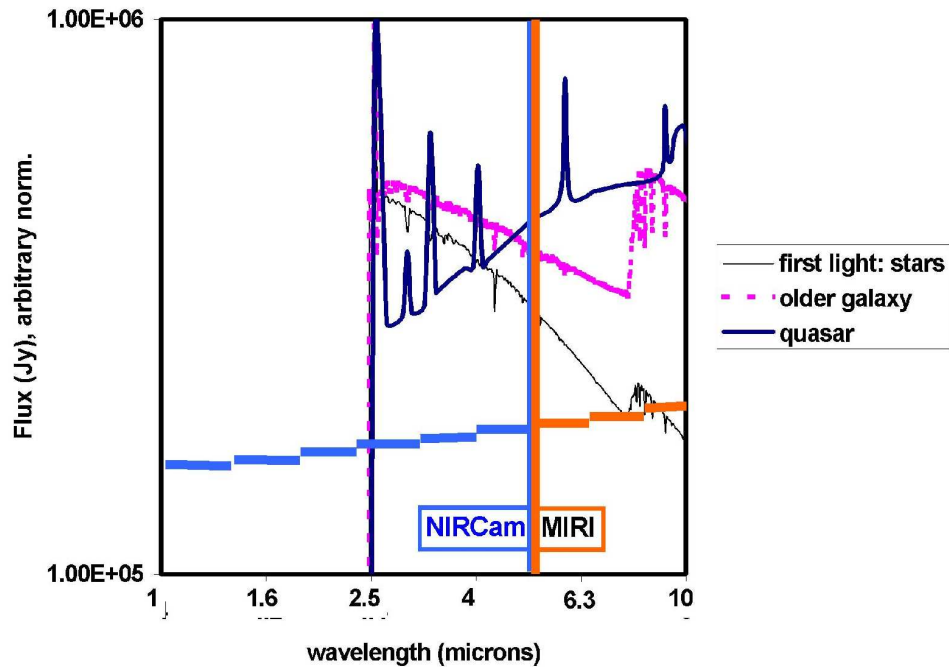
How can HST & JWST measure Galaxy Assembly & SMBH/AGN Growth?



● Can't beat redshift: to see First Light, must observe near-mid IR.

⇒ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–29 μm .

● (1b) What sensitivity will JWST have?

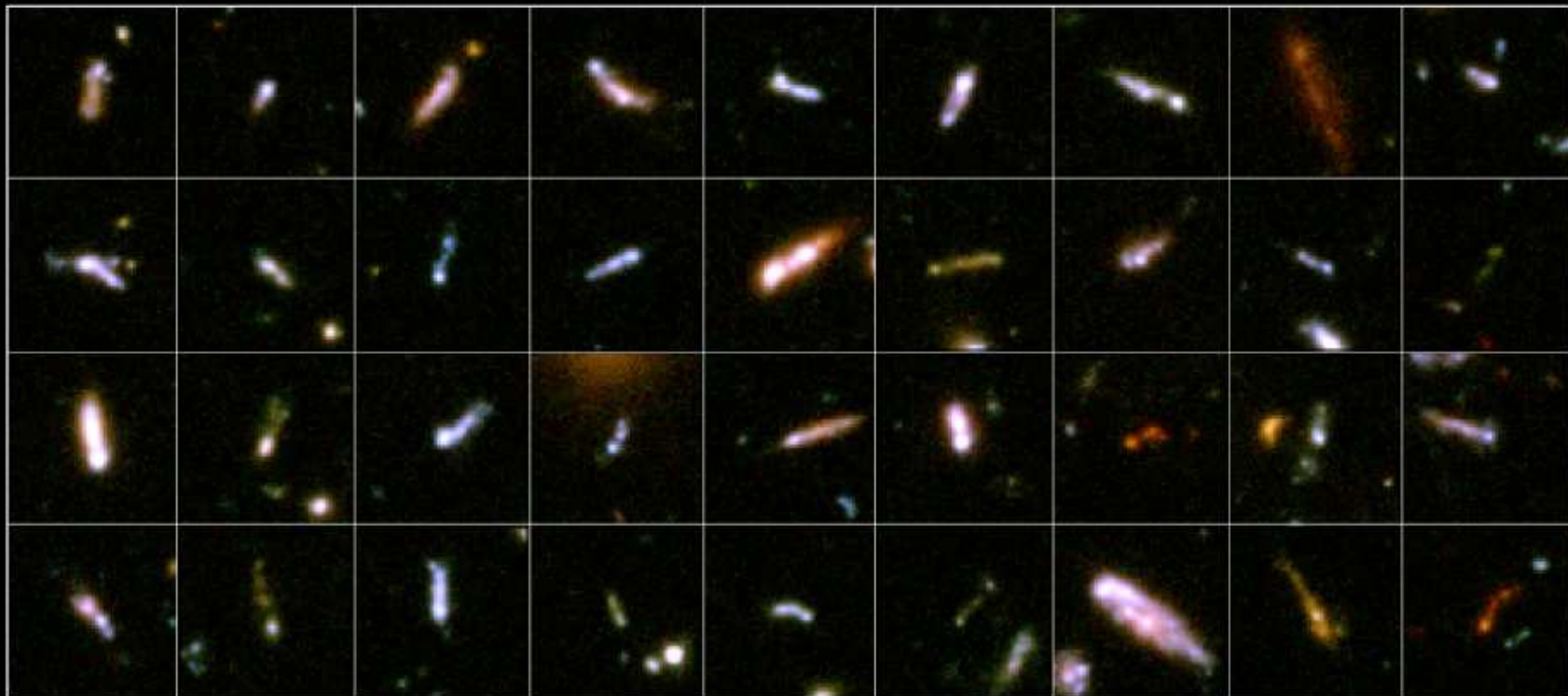


NIRCam and MIRI sensitivity complement each other, straddling $\lambda \simeq 5 \mu\text{m}$. Together, they allow objects to be found to $z=15-20$ in $\sim 10^5$ sec (28 hrs).

LEFT: NIRCam and MIRI broadband sensitivity to a Quasar, a “First Light” galaxy dominated by massive stars, and a 50 Myr “old” galaxy at $z=20$.

RIGHT: Relative survey time vs. λ that Spitzer, a ground-based IR-optimized 8-m, and a 30-m telescope would need to match JWST.

(2) A study of Early-Stage Mergers in the HUDF: Any AGN?



“Tadpole” Galaxies in the Hubble Ultra Deep Field
Hubble Space Telescope ■ ACS/WFC

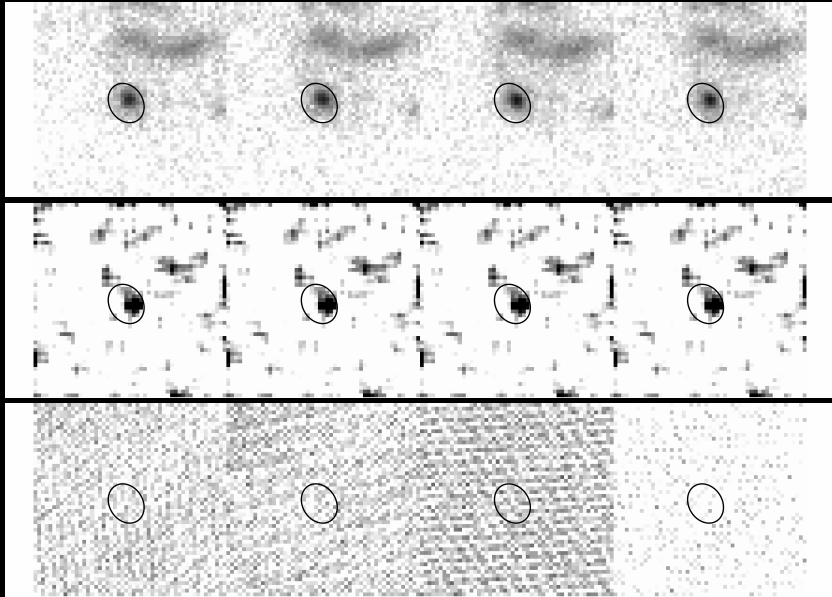
NASA, ESA, A. Straughn, S. Cohen and R. Windhorst (Arizona State University), and the HUDF team (STScI)

STScI-PRC06-04

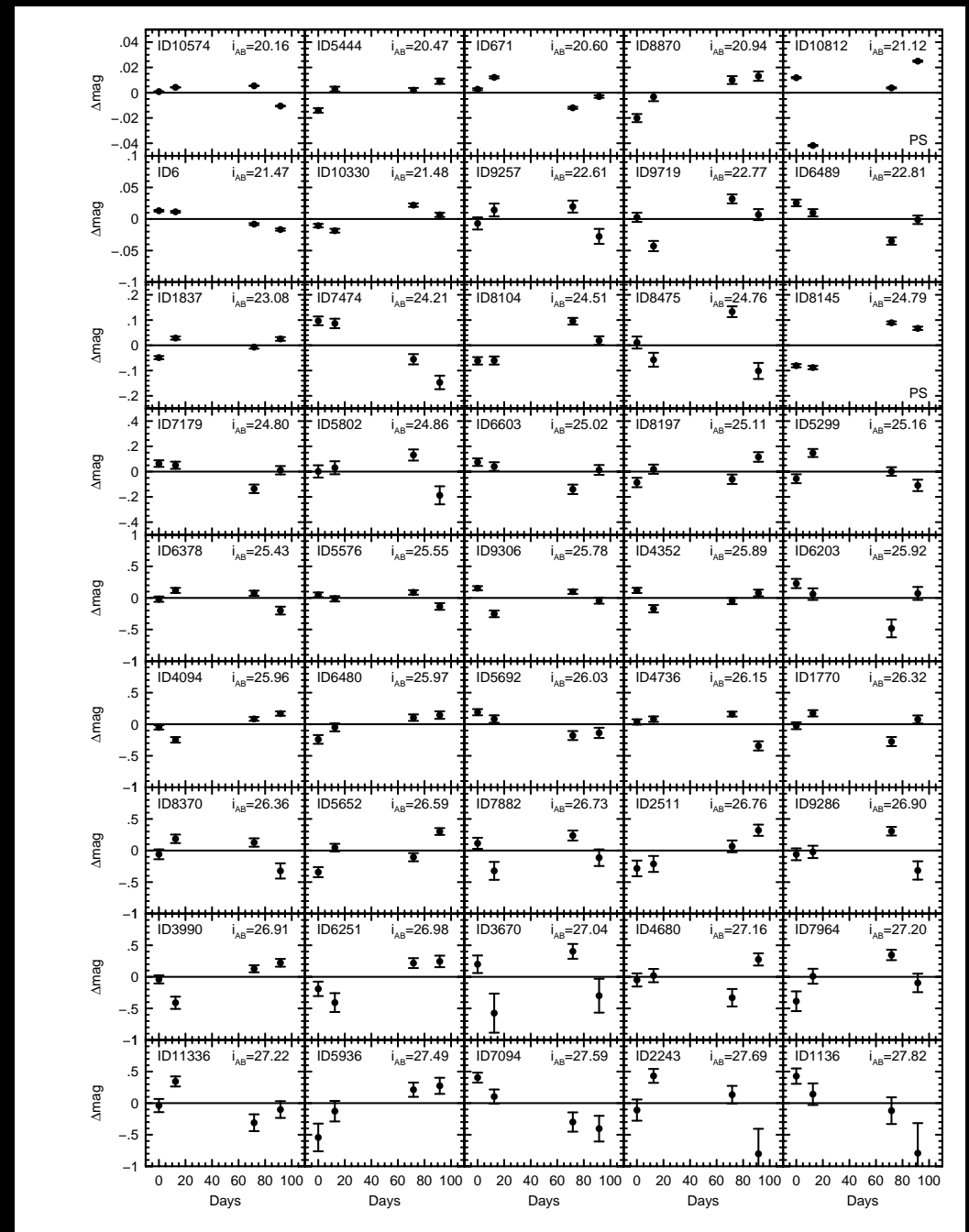
Tadpole galaxies in HUDF: www.hubblesite.org/newscenter/archive/2006/04/

Straughn, A. N., et al. 2006, *ApJ*, 639, 724 (astro-ph/0511423)

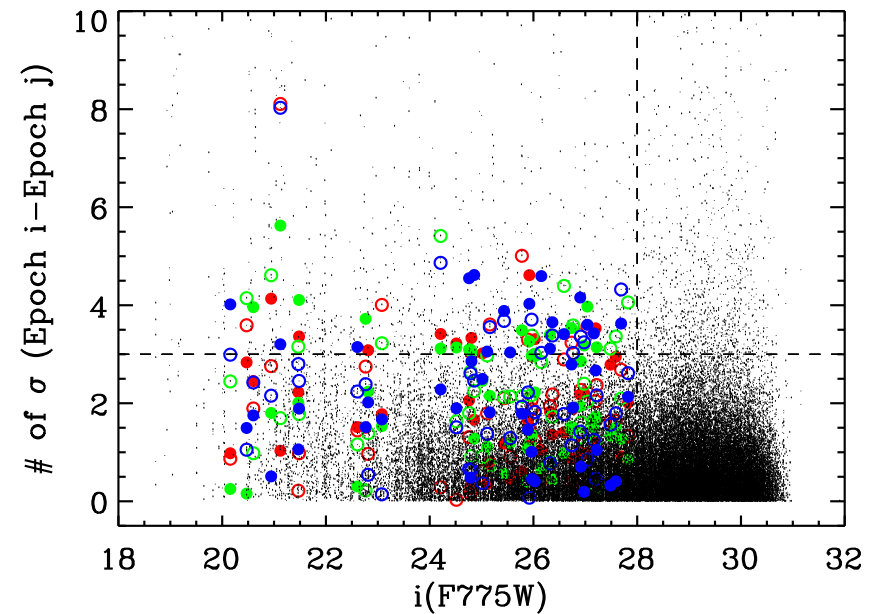
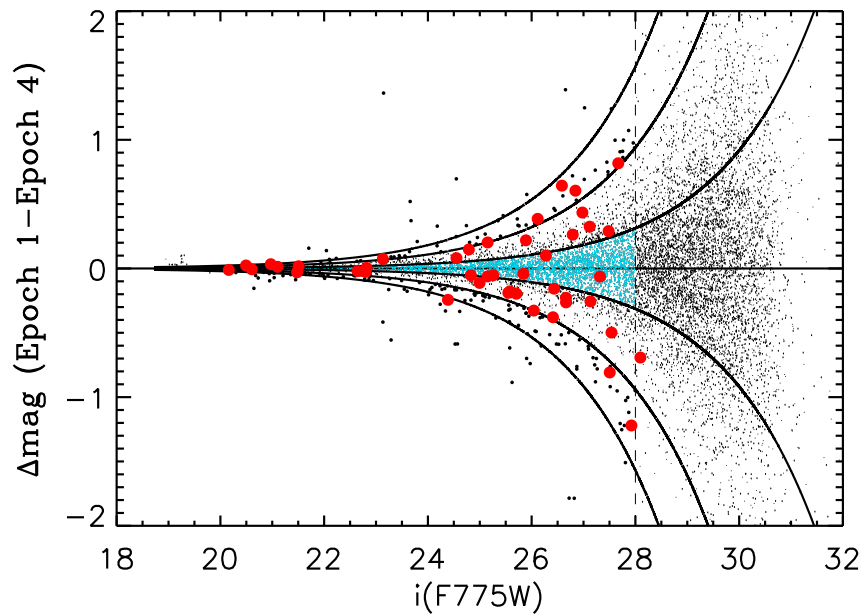
(3) Variable Objects in the HUDF



Top: 4 epochs; Middle: Variance map; Bottom: 4 Weight-maps.
(Cohen, S., et al. 2006, ApJ, 639, 731; astro-ph/0511414)



Light curves: Can detect bright HUDF variable objects on timescales of days–months, even if $|\Delta\text{mag}|(t) \lesssim 1\text{--}2\%$!



Flux ratio of all objects between two HUDF epochs ($\Delta t \simeq$ few weeks–months) vs. total i-band flux. Lines are at $\pm 1.0\sigma$ (blue), $\pm 3.0\sigma$, $\pm 5.0\sigma$.

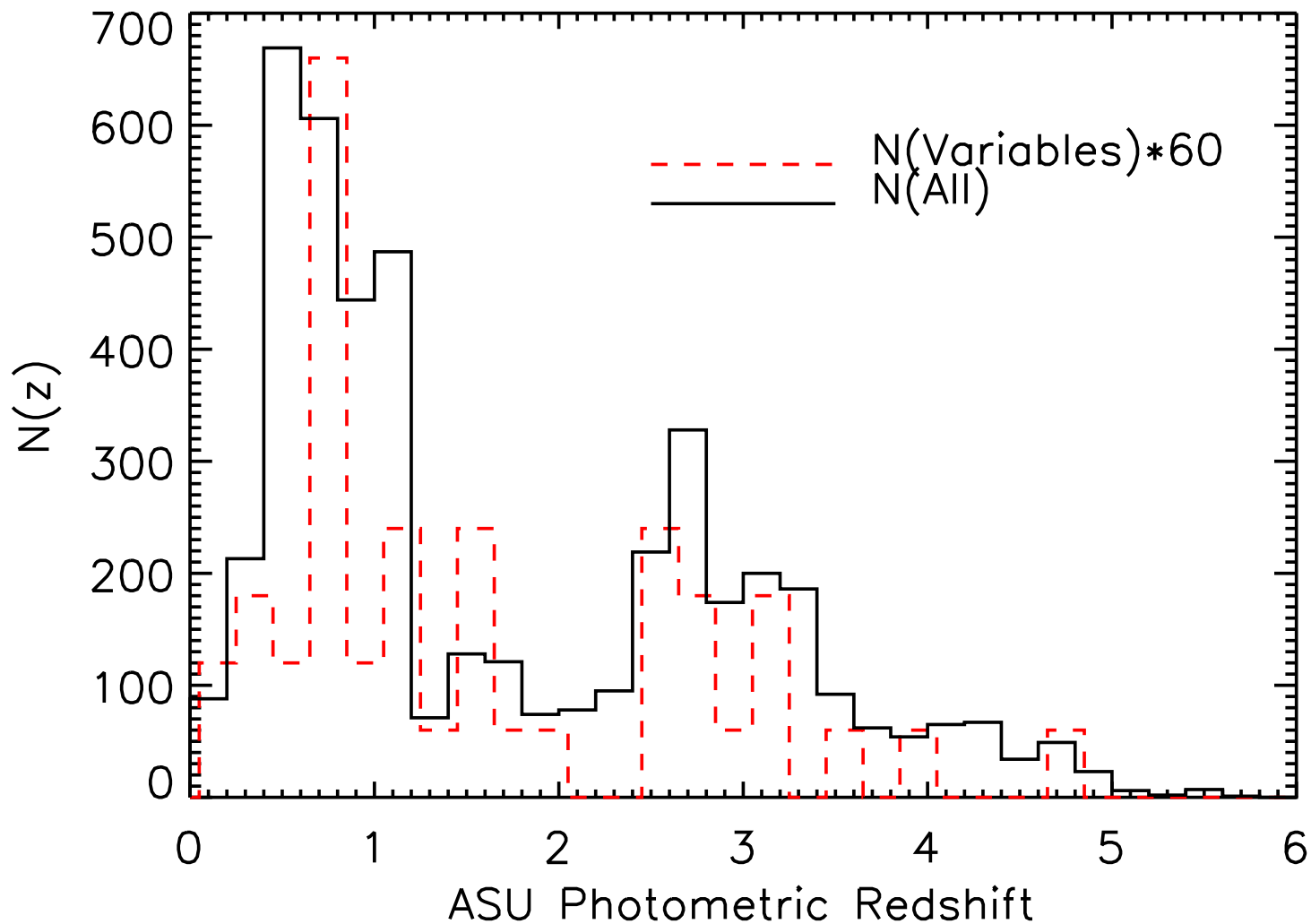
- Objects with $|\Delta \text{mag}| \geq 3.0\sigma$ in ≥ 2 epoch-pairs are variable.

- 3 out of 16 Chandra sources are faint point-like objects variable at $\gtrsim 3.0\sigma$; other Chandra sources are brighter (early-type) galaxies.

\Rightarrow Variable point sources are valid AGN candidates:

- $\sim 1\%$ of all HUDF galaxies have weak variable AGN.

- We only sample $\Delta \text{Flux} \gtrsim 10\text{—}30\%$ on timescales of months. This AGN sample is not complete — we miss all non-variable and obscured AGN.

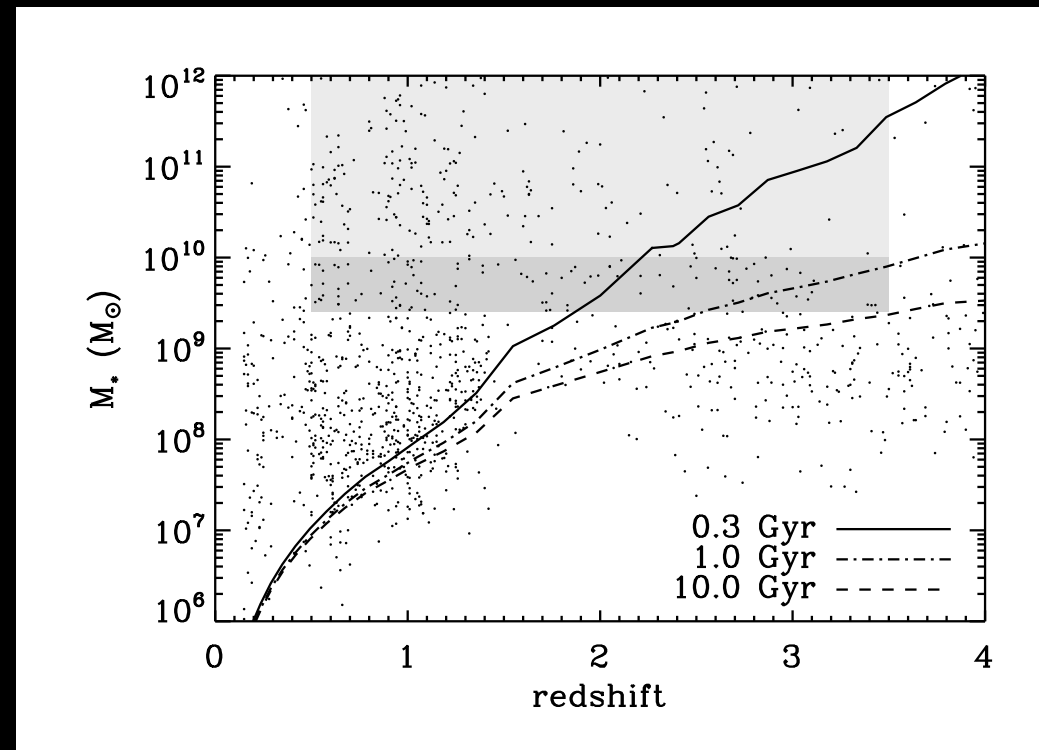
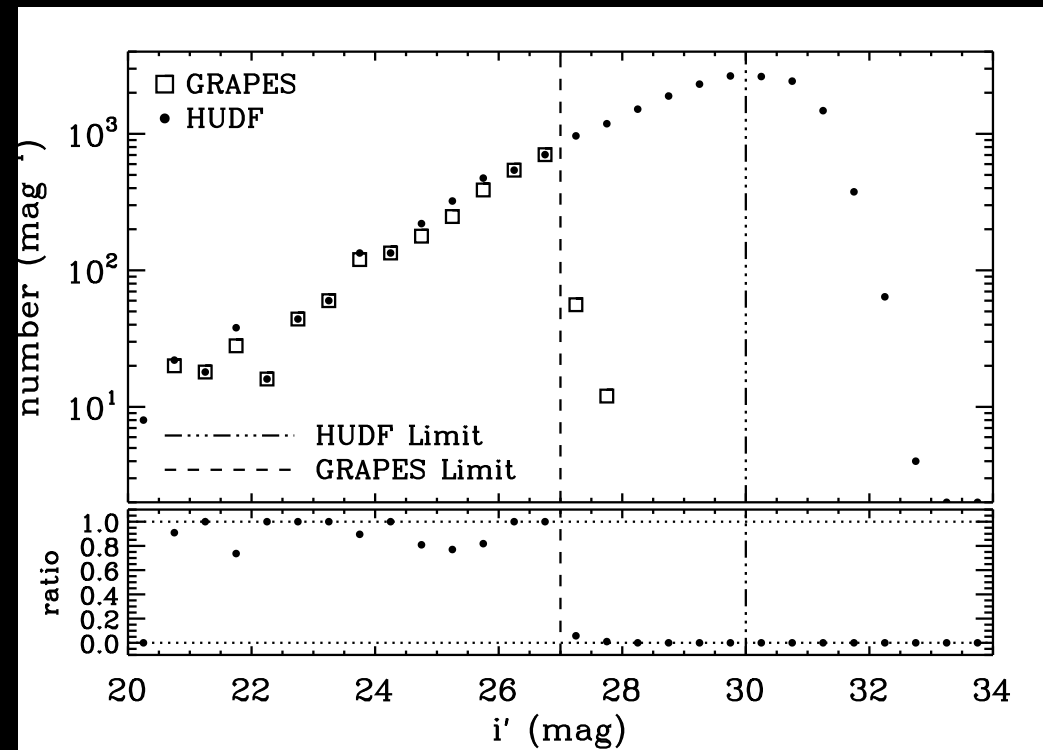


BViz(JH) Photo-z distribution of HUDF field gxy's and variable objects:

- Variable objects show a similar $N(z)$ as field galaxies. About 1% of all field galaxies have variable weak AGN at all redshifts.

⇒ If variable objects are representative of all weak AGN, SMBH growth keeps pace with the cosmic SFR (which peaks at $z \simeq 1-2$).

(4) Epoch dependent major merger rate to $AB \lesssim 27$ mag.



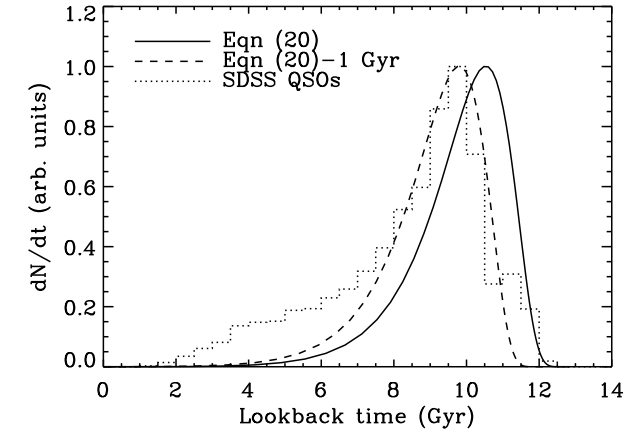
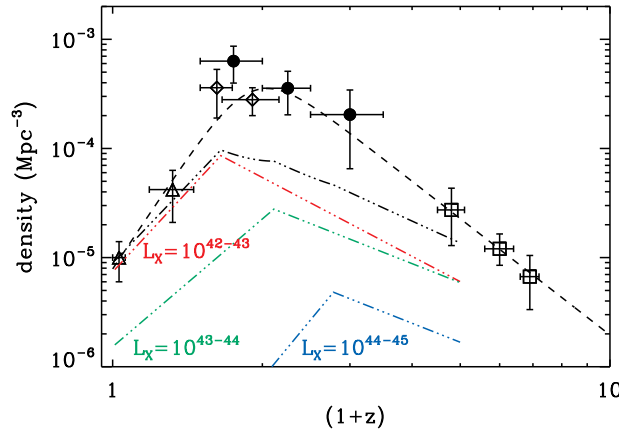
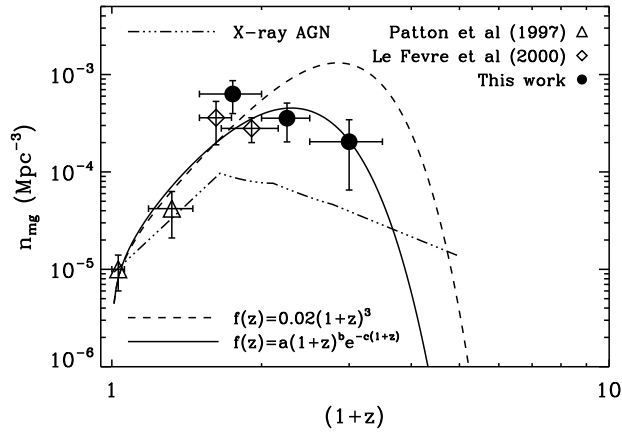
Ryan et al. (2007): HST/ACS grism pair-fraction(z) — sample selection:

- HUDF broad-band point source completeness at $i_{AB} \lesssim 30.0$ mag.
- HUDF ACS grism point source completeness at $i_{AB} \lesssim 27.0$ mag.

Mass completeness limit for $z \lesssim 2$ from flux limits/SED fitting:

- $M \gtrsim 10^{10.0} M_\odot$ for primary galaxy mass in pair.
- $M \gtrsim 10^{9.4} M_\odot$ for secondary galaxy mass in pair ($0.25 \leq M_2/M_1 \leq 1$).

(4) Epoch dependent major merger rate to $AB \lesssim 27$, X-ray $n(z)$



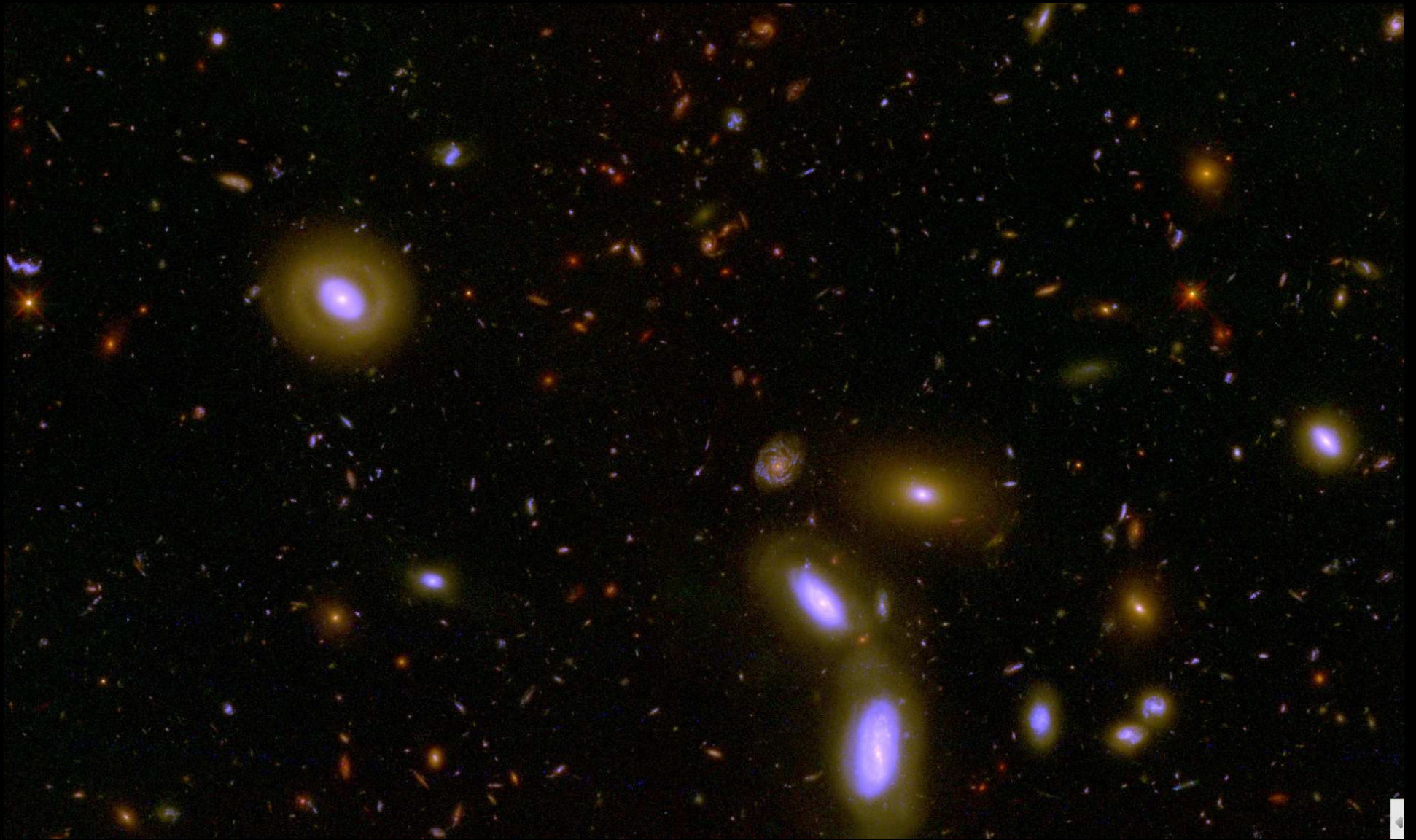
Ryan et al. (2007, 2008): HST/ACS grism epoch-dependent galaxy pair-fraction for $AB \lesssim 27$, $z \lesssim 6$: spectro-photo- z 's for both objects in pair. Merger samples are very complex to select (Lotz et al. 2009).

Galaxy major ($0.25 \leq M_2/M_1 \leq 1$) merger density compared to Chandra SDSS QSO density vs. z : Similar curves, but with a ~ 1 Gyr offset??

\Rightarrow Circumstantial support for hierarchical models: a ~ 1 Gyr delay between major mergers & visible SMBH feeding — weak AGN?

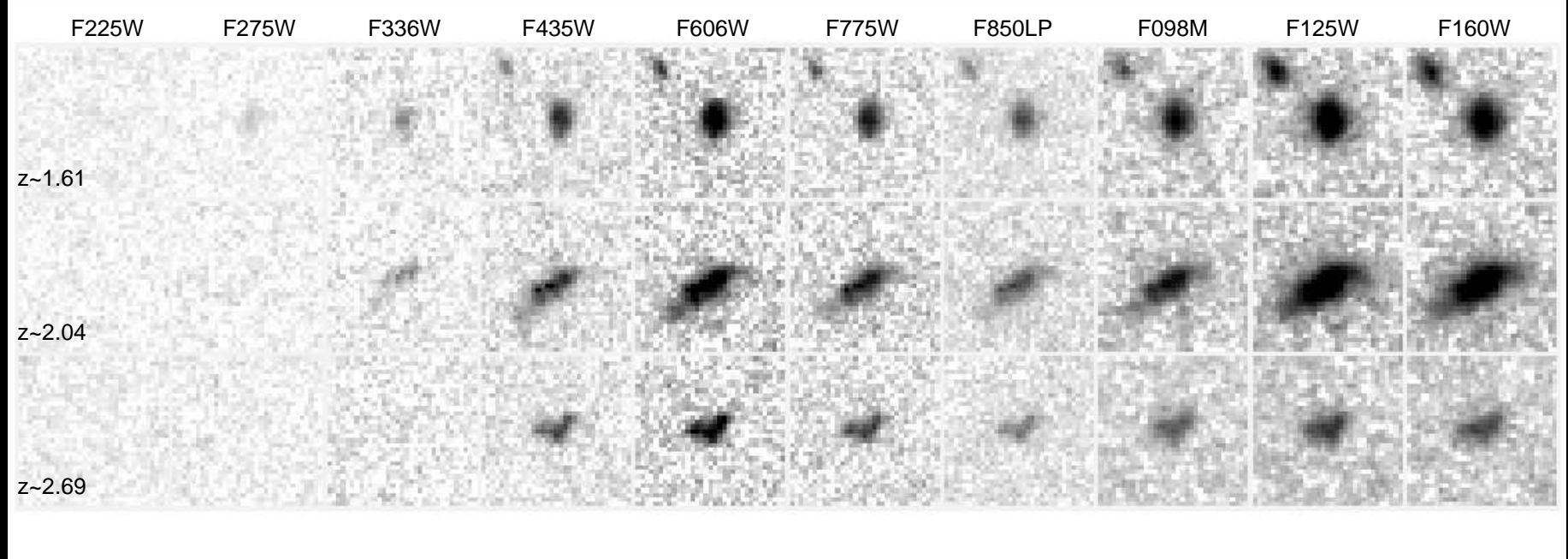
● JWST will be able to do this 3 mag fainter, from $0.7\text{--}5.0 \mu\text{m}$, sampling rest-frame UV-optical for $z \simeq 0\text{--}20$.

- (5) Can we DIRECTLY trace weak AGN growth with WFC3 and JWST?

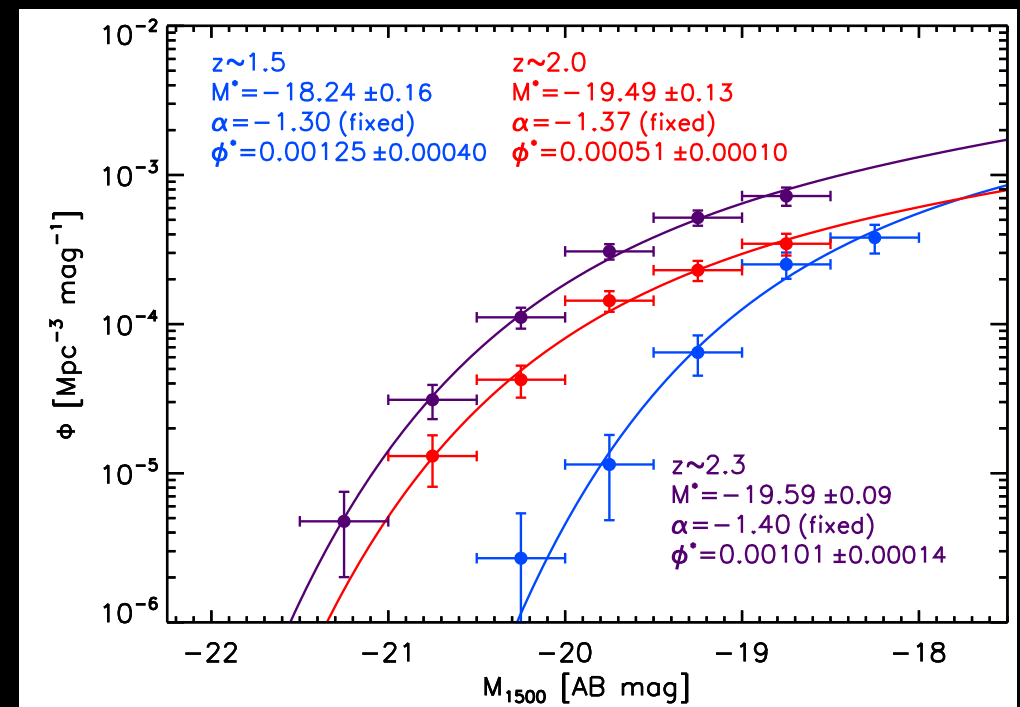
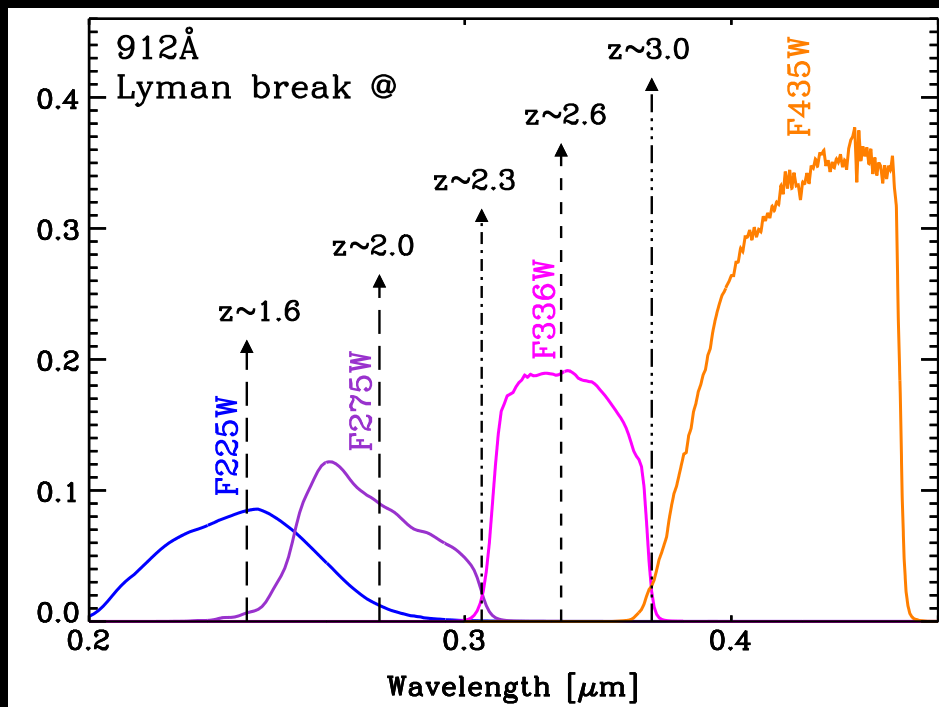


10 filters with HST/WFC3 & ACS reaching $AB=26.5-27.0$ mag ($10-\sigma$) over 40 arcmin^2 at $0.07-0.15''$ FWHM from $0.2-1.7 \mu\text{m}$ (UVUBVizYJH).

JWST adds $0.05-0.2''$ FWHM imaging to $AB \simeq 31.5$ mag (1 nJy) at $1-5 \mu\text{m}$, and $0.2-1.2''$ FWHM at $5-29 \mu\text{m}$, tracing young+old SEDs & dust.

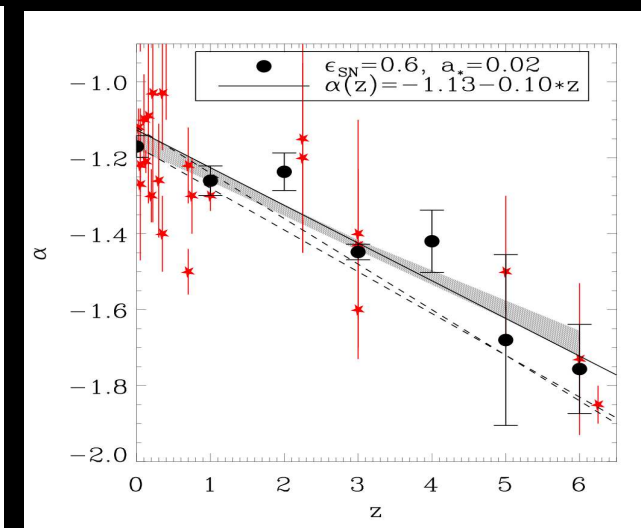
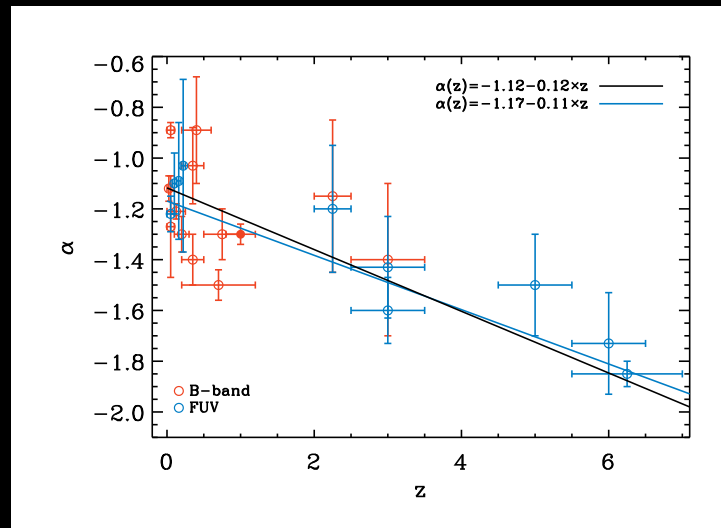
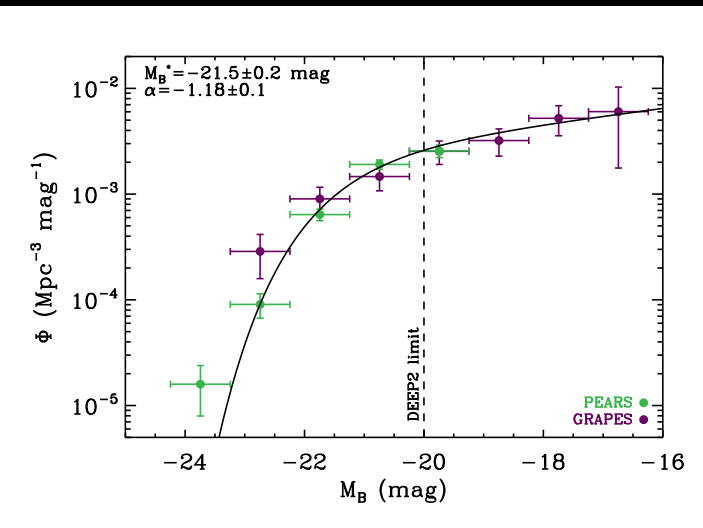


WFC3 Lyman break galaxies at the peak of cosmic SF ($z \simeq 1-3$; Hathi⁺ 2010)



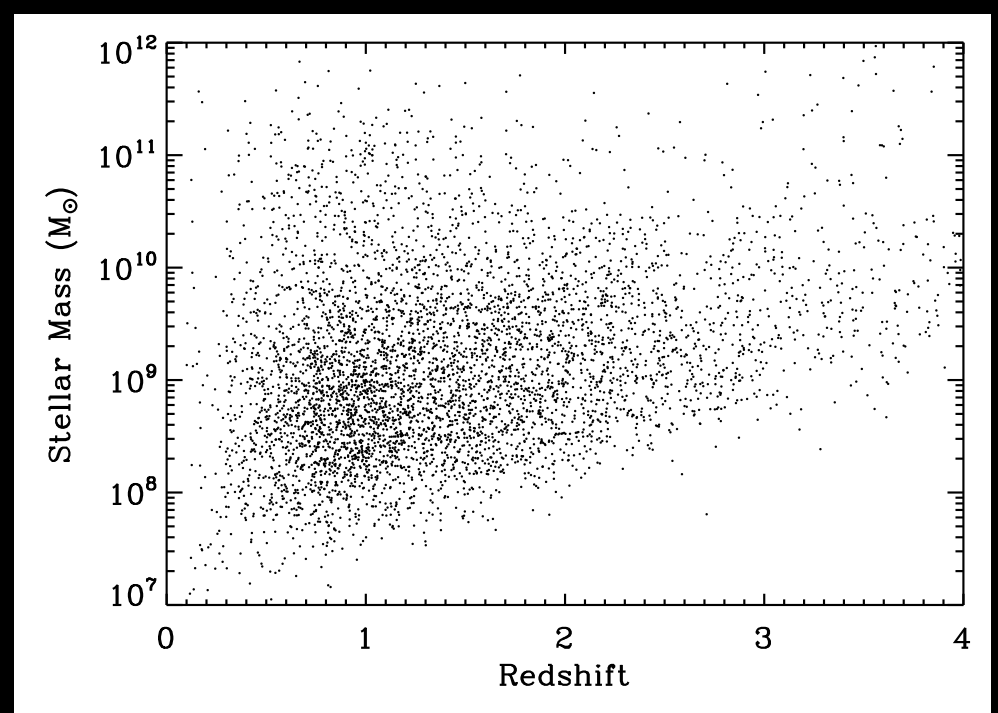
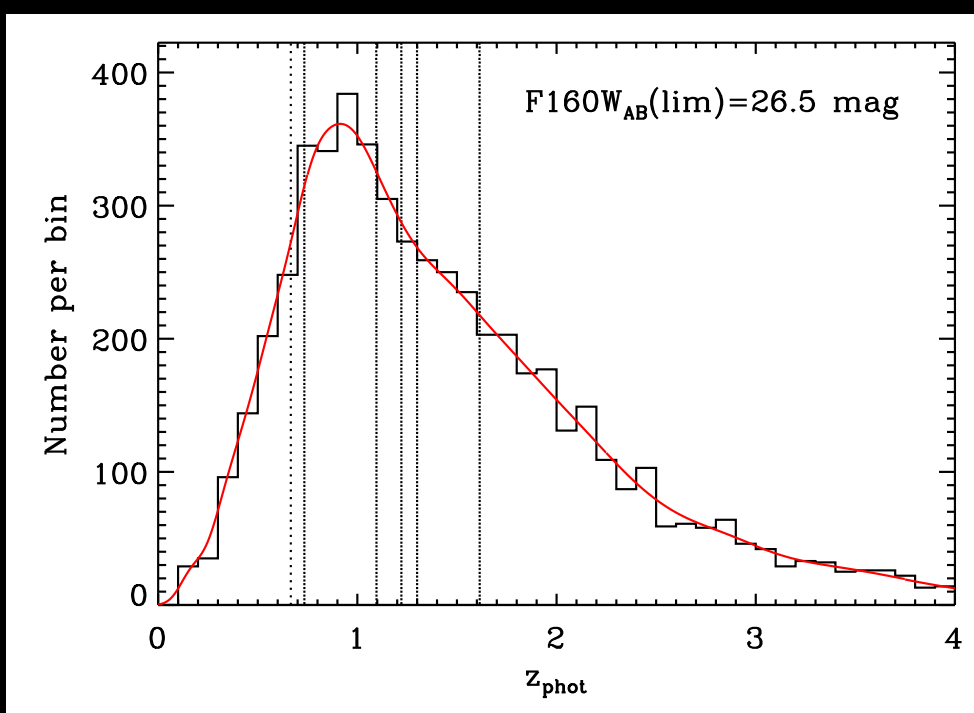
- JWST will similarly measure faint-end LF-slope evolution for $1 \lesssim z \lesssim 12$.

Faint-end LF-Slope Evolution (fundamental, like local IMF)



Faint-end LF-slope at $z \gtrsim 1$ with accurate ACS grism z 's to $AB \lesssim 27$ (Cohen et al.; Ryan et al. 2007, ApJ, 668, 839) constrains hierarchical formation:

- Star-formation and SN feedback produce different faint-end slope-evolution: new physical constraints (Khochfar et al. 2007, ApJL, 668, L115).
- JWST will provide fainter spectra ($AB \lesssim 29$) and spectro-photometric redshifts to much higher z ($\lesssim 20$). JWST will trace α -evolution for $z \lesssim 12$.
- Can measure environmental impact on faint-end LF-slope α directly.



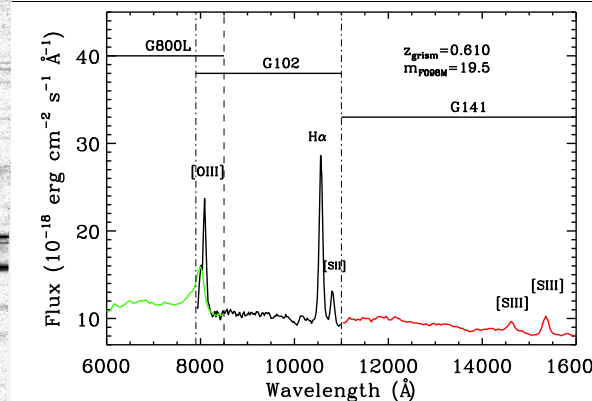
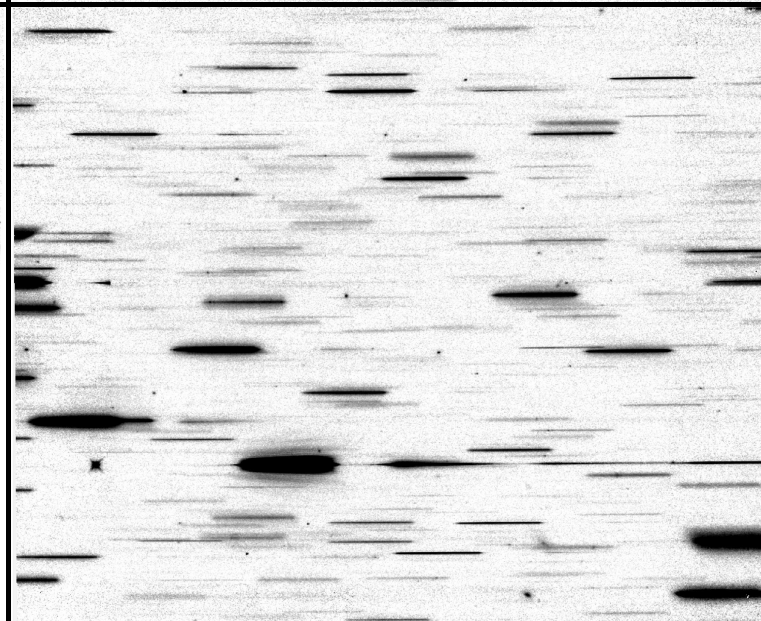
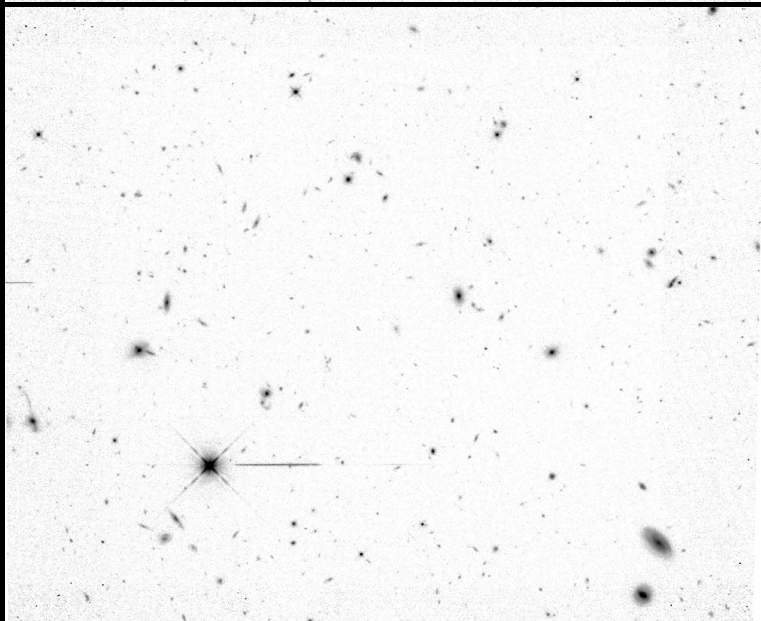
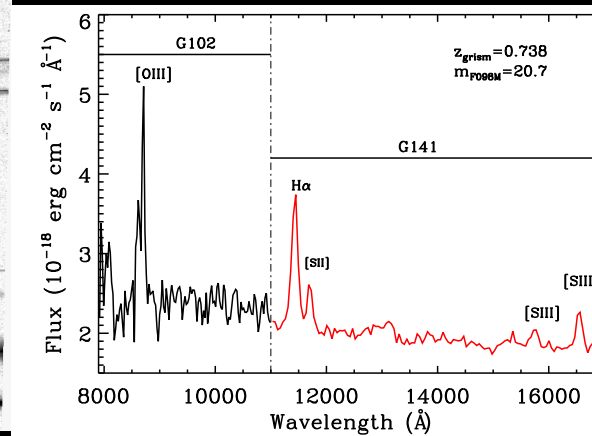
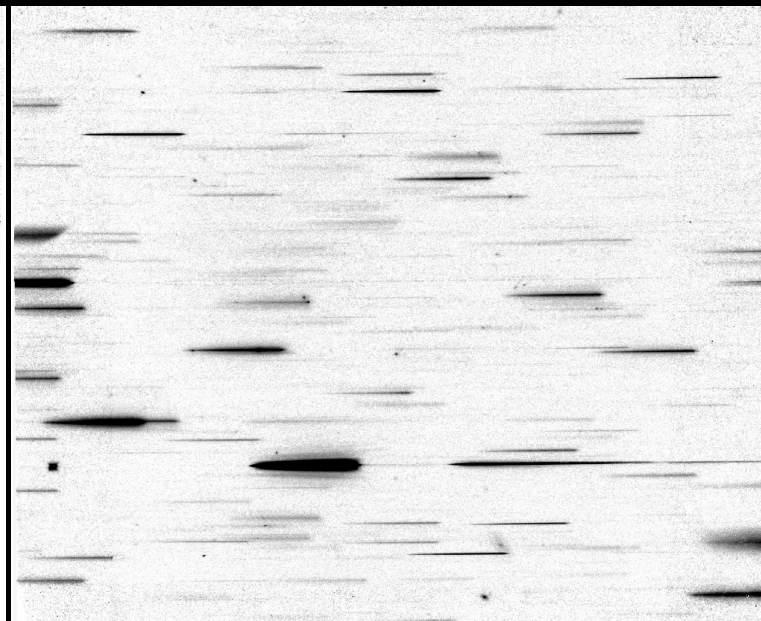
WFC3 ERS 10-band redshift estimates accurate to $\sim 4\%$ with small systematic errors (Cohen et al. 2010), resulting in a reliable redshift distribution.

- Reliable masses of faint galaxies to $AB=26.5 \text{ mag}$, accurately tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?)

ERS shows WFC3's new panchromatic capabilities on galaxies at $z \simeq 0-7$.

- HUDF shows WFC3 $z \simeq 7-9$ capabilities (Bouwens⁺ 2010; Yan⁺ 2010.

⇒ WFC3 is an essential pathfinder at $z \lesssim 8$ for JWST ($0.7-29 \mu\text{m}$) at $z \gtrsim 9$.



HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn⁺ 2010)

IR grism spectra from space: unprecedented new opportunities in astrophysics.

JWST will provide near-IR grism spectra to $AB \lesssim 29$ mag from $2-5.0 \mu\text{m}$.

(5) Radio & X-ray host SED-ages: trace AGN growth directly?

[1] DATA: HST GOODS BVizJHK photometry and VLT JHK + redshifts.

[2] METHOD: SED fitting for $0.12 \lesssim \lambda_{rest} \lesssim 1.6 \mu\text{m}$, using:

- (a) Bruzual-Charlot (2007) stellar population models.
- (b) + AGN power law $S_\nu \propto \nu^\alpha$ bluewards of the IR dust emission.
- VLT redshifts for all objects $AB \lesssim 24-25$ (Le Fèvre et al. 2004; Szokoly et al. 2004; Vanzella et al. 2005, 2008; see www.eso.org/science/goods/)

For typical $z \simeq 0.5-1.5$, BVizJHK bracket the Balmer+4000Å breaks.

[3] SED fitting:

- Use solar metallicity and Salpeter IMF (most objects at $z \lesssim 2$).
- E-folding times τ in log spaced $n=16$ grid from 0.01-100 Gyr.
- $n=244$ ages \lesssim age of Universe at each redshift in WMAP-cosmology.
- Calzetti et al. dust extinction: $A_V = [0, 4.0]$ in 0.2 mag steps ($n=21$).
- $\alpha = [0, 1.5]$ in steps of 0.1 ($n=16$ values).

[4] Yields $\sim 10^6$ models for 1549 GOODS galaxies with VLT redshifts.

Best χ^2 fit stellar mass + possible AGN UV–optical power-law component.

Method follows Windhorst et al. (1991, 1994, 1998), where HST + ground-based UBgriJHK images showed non-negligible AGN components in mJy radio galaxies.

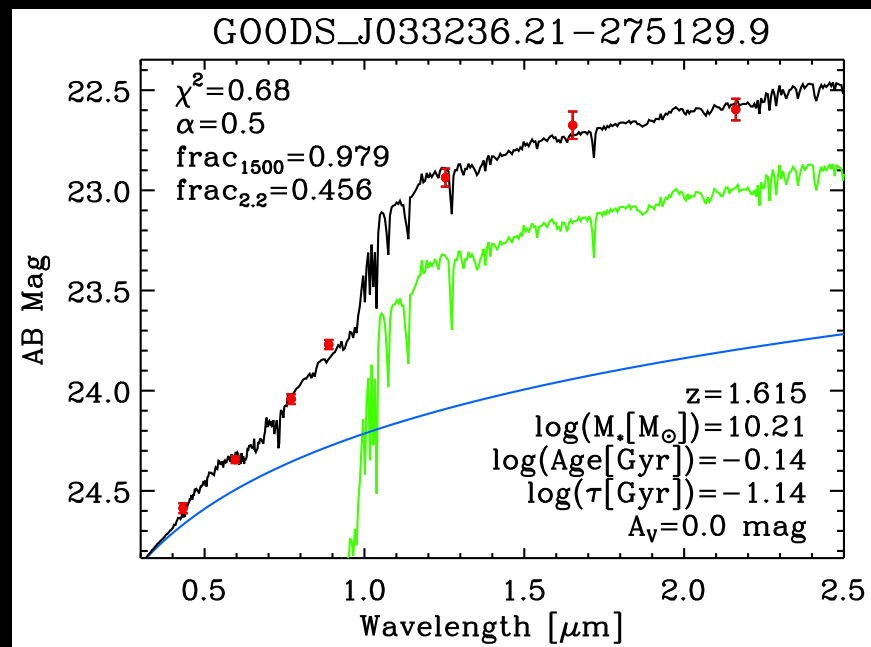
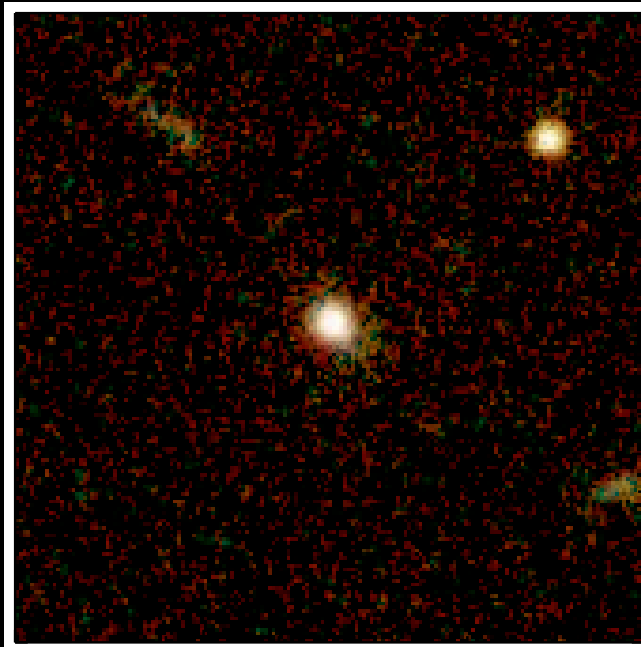
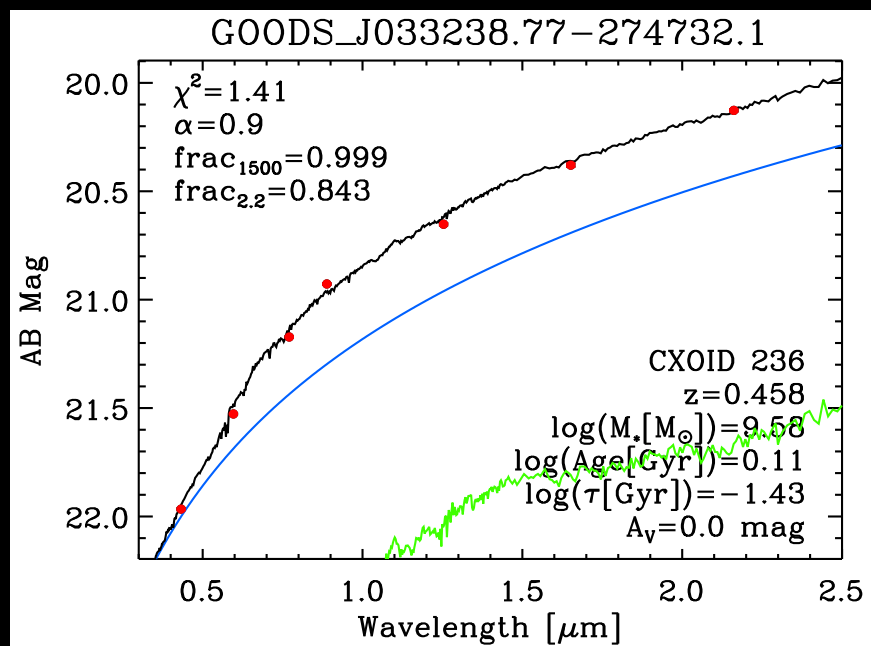
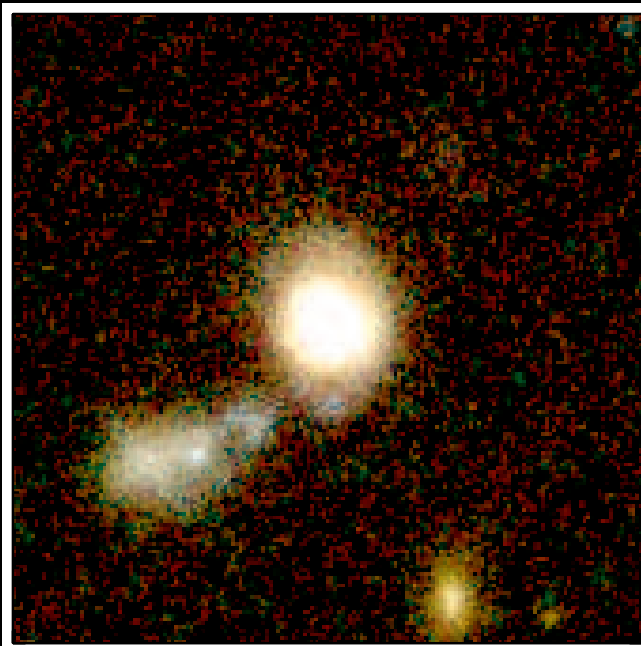
[5] Work in progress on other potential caveats:

- Young stellar populations have power-law UV spectra (Hathi et al. 2008), and may overestimate UV AGN power-law.

- Include IRAC data and incorporate 1–2 Gyr red AGB population.

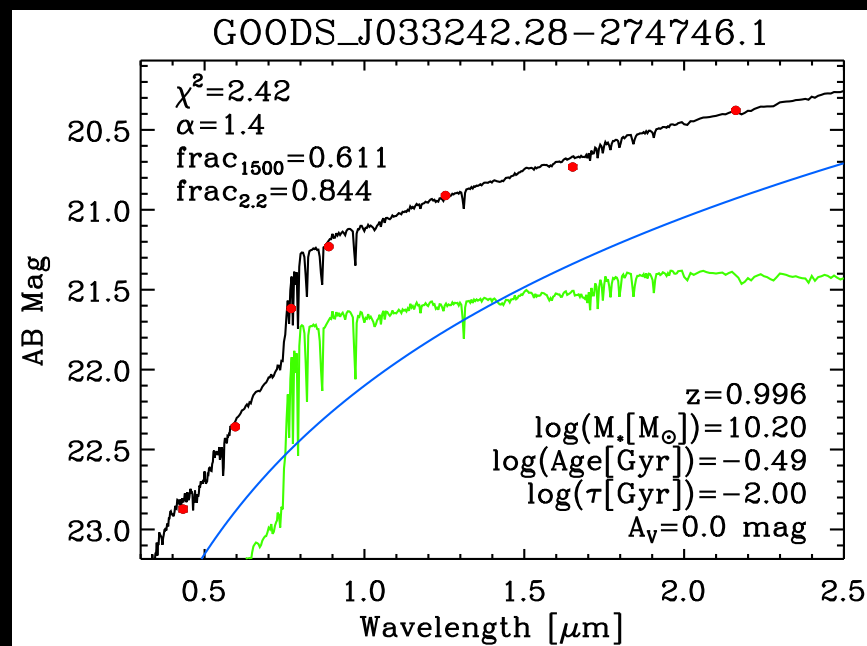
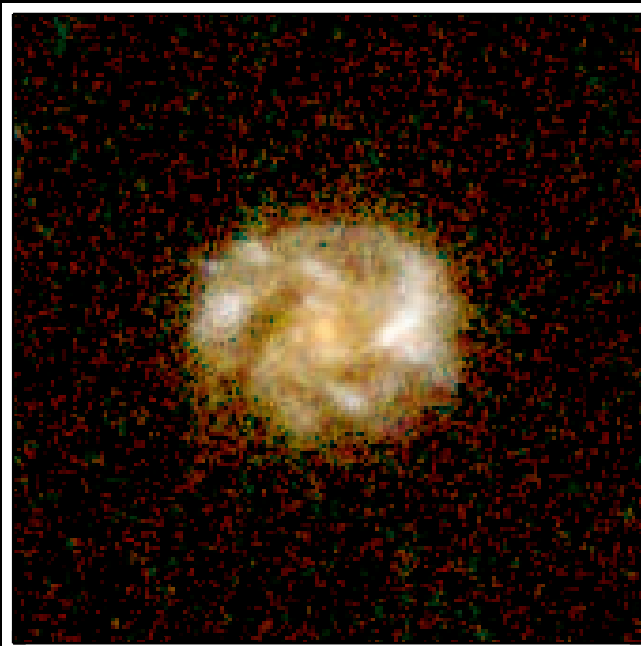
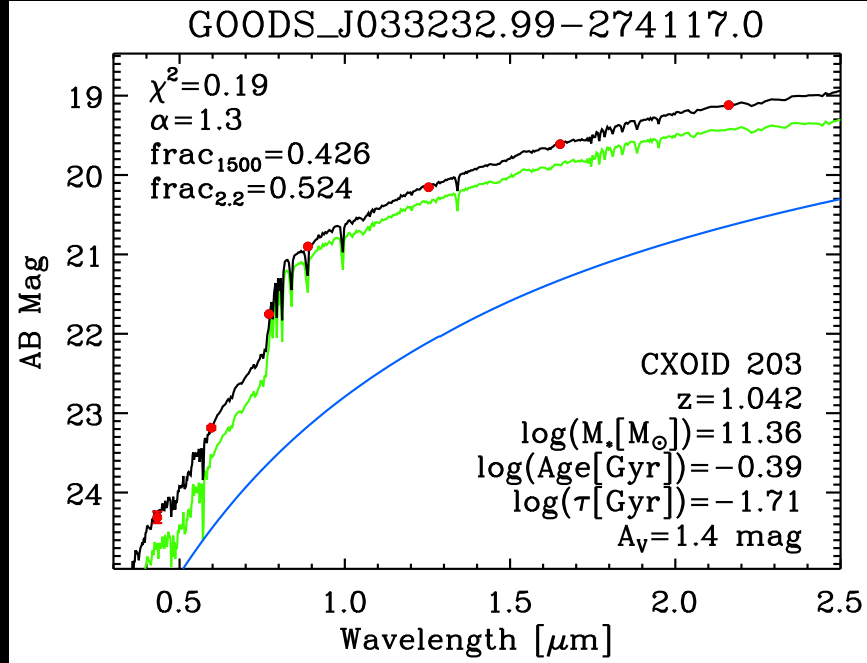
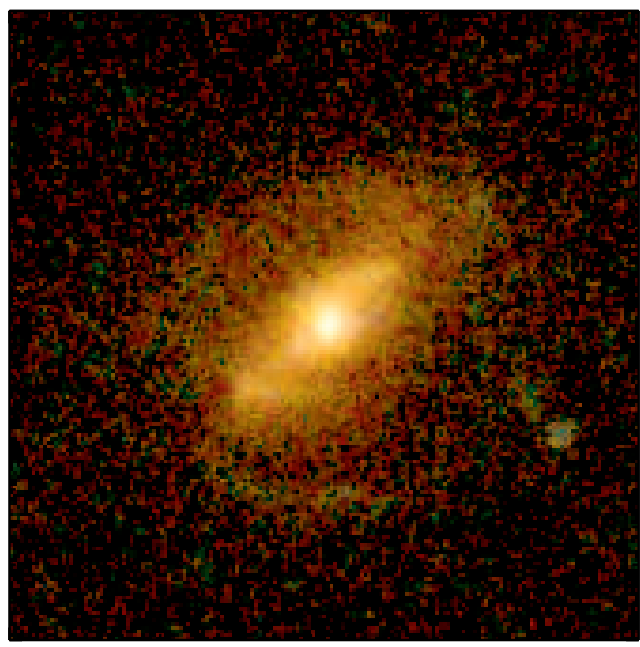
[6] Repeat [1]–[5] for 7000 ERS objects with 10-band spz's to AB=27 mag.

- Fit the BC03 stellar SED only to objects where χ^2 doesn't require both.



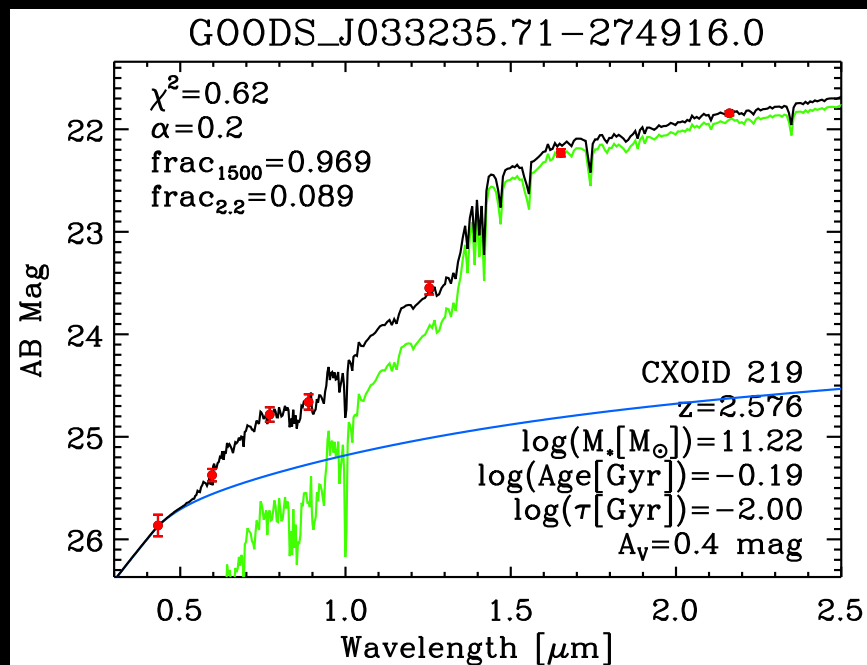
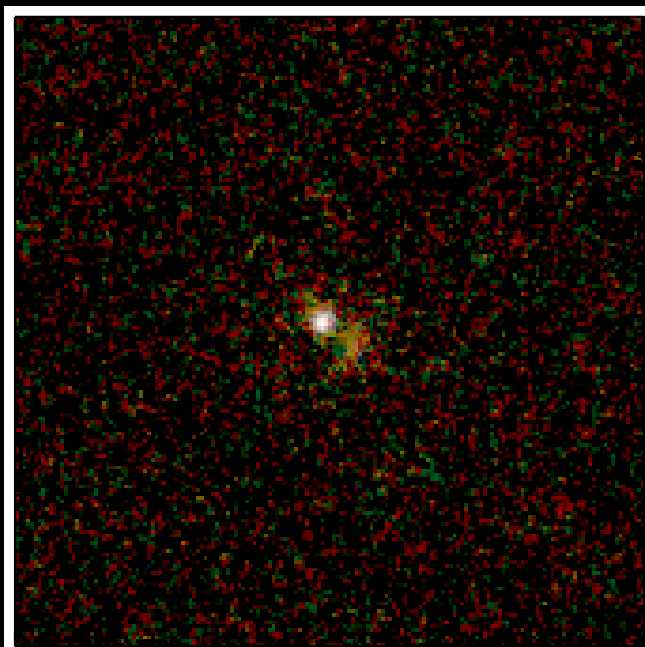
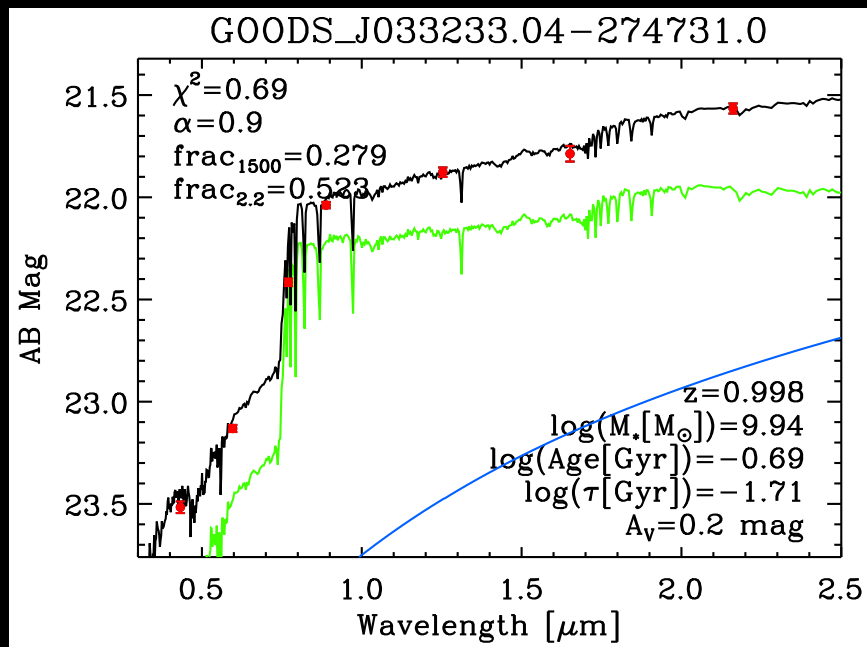
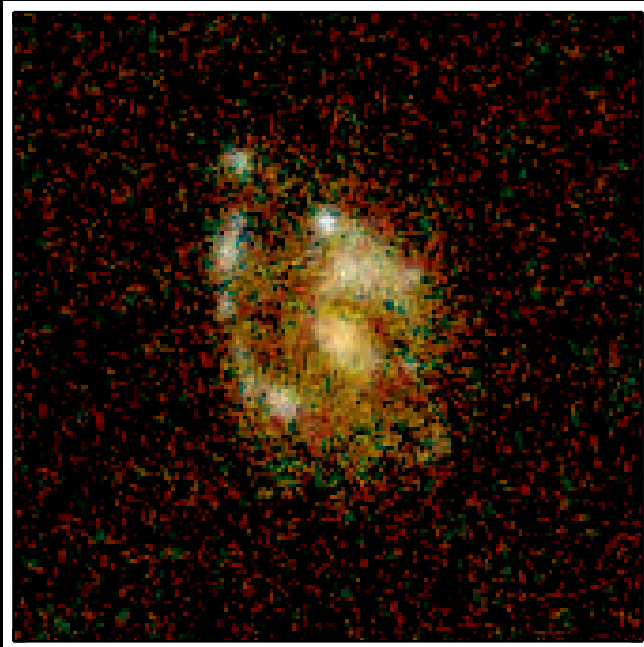
Cohen et al. (2010): GOODS/VLT BVizJHK images

Best fit Bruzual-Charlot (2003) SED + power law AGN.

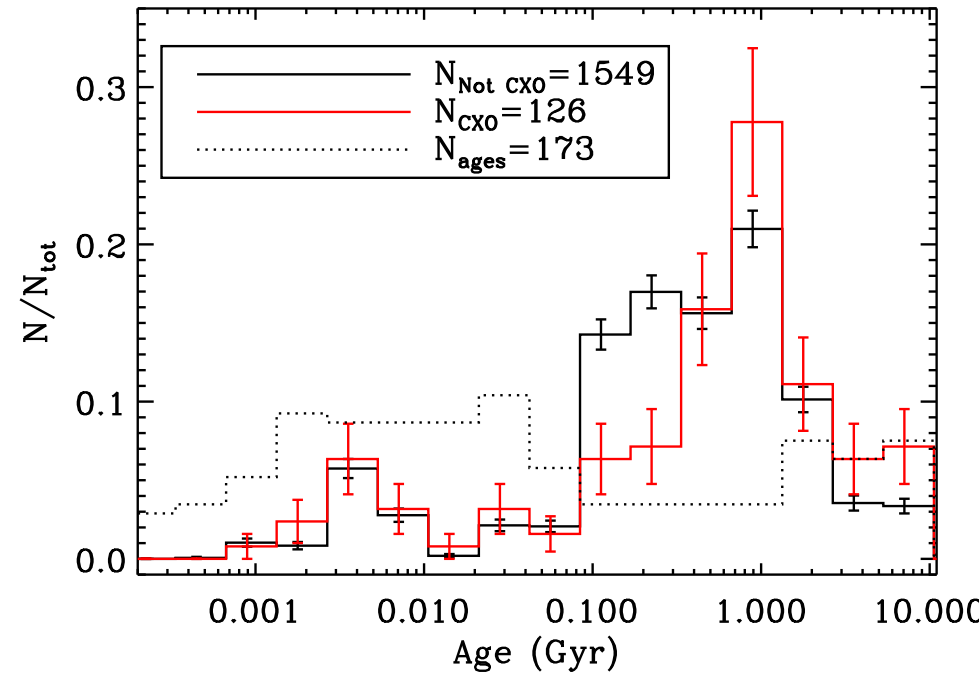
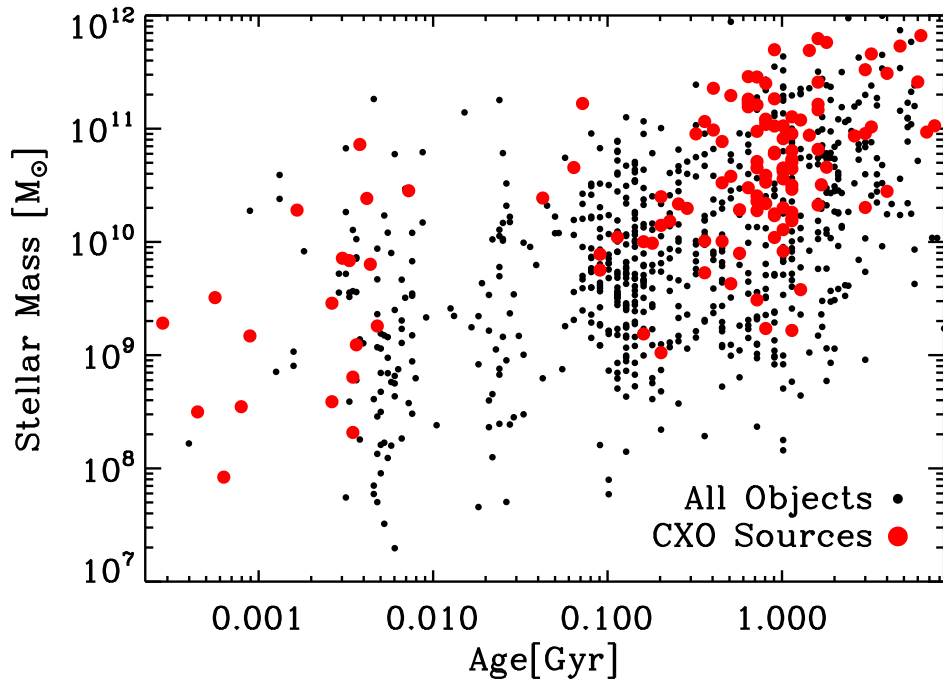


Cohen et al. (2010): GOODS/VLT BVizJHK images

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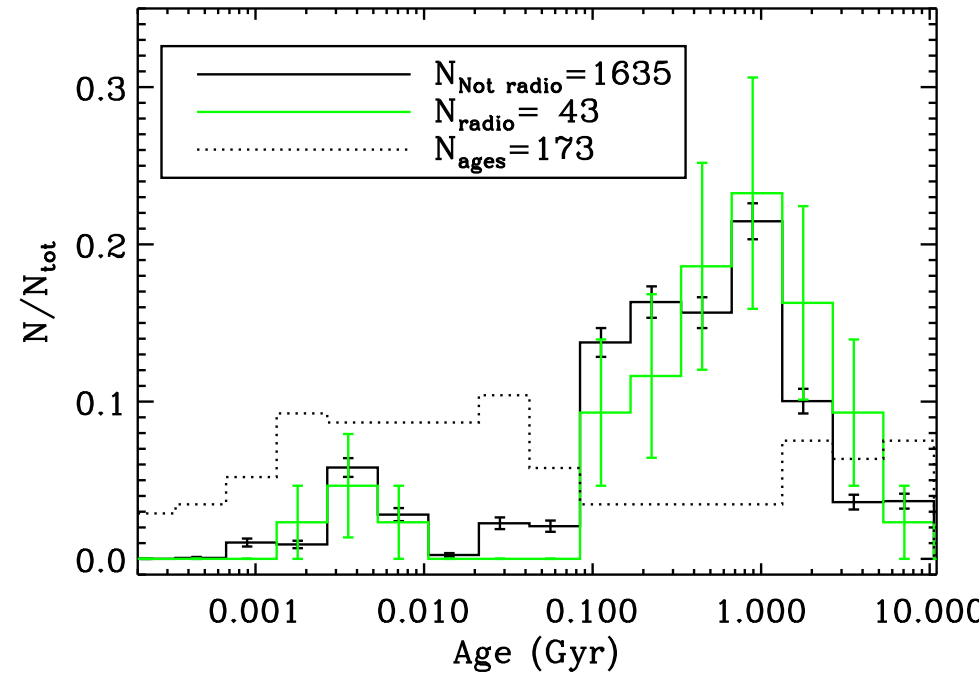
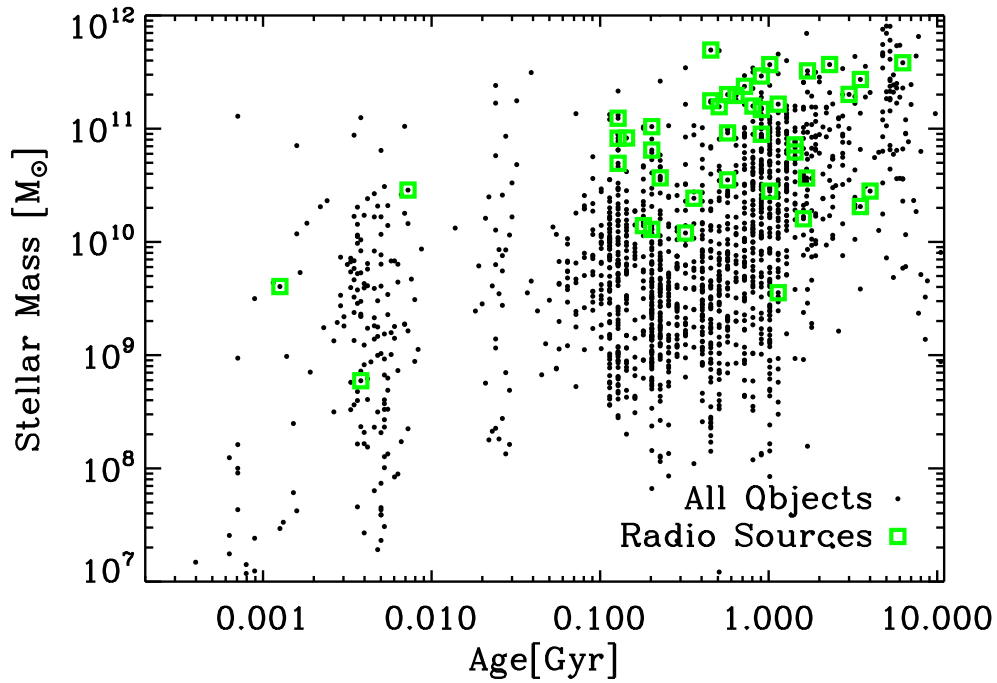
Cohen et al. (2010): Best fit Stellar Mass vs. Age: X-ray and field galaxies.

Field galaxies have: Blue cloud of ~ 100 -200 Myr, Red cloud of $\gtrsim 1$ -2 Gyr.

- X-ray sources reside in galaxies that are a bit older than the general field population, but by no more than $\lesssim 0.5$ -1 Gyr on average.

- JWST+WFC3 can disentangle multiple SED + AGN power-law from 15-band photometry to AB=30 mag for $z \lesssim 10$.

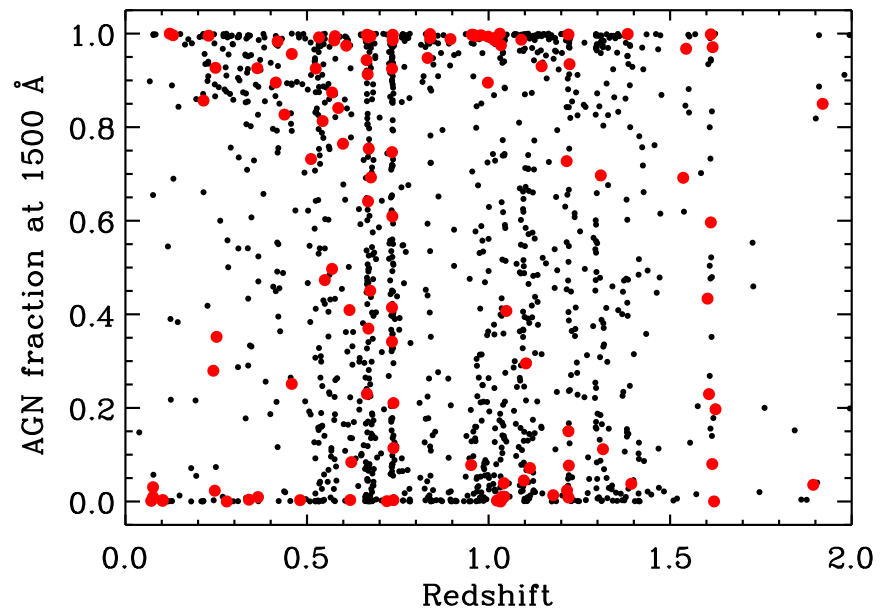
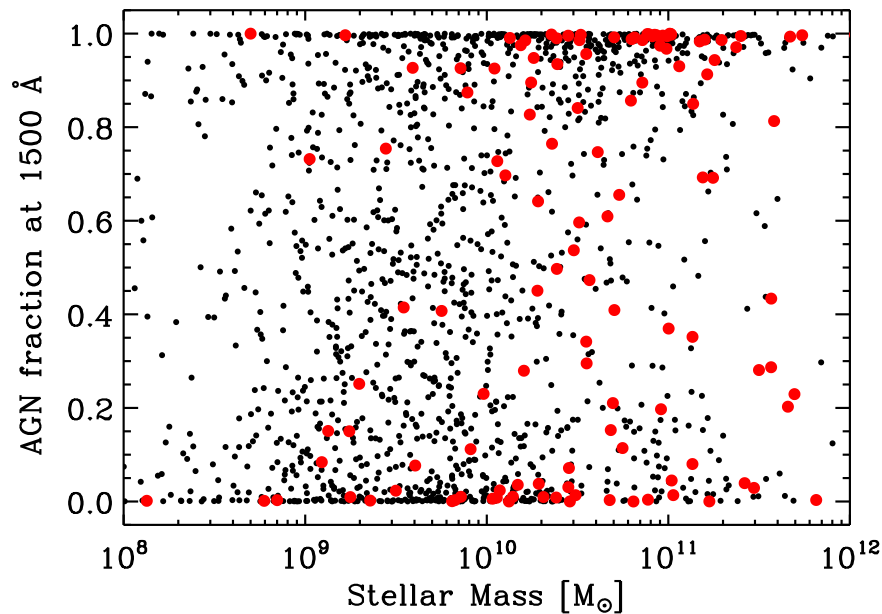
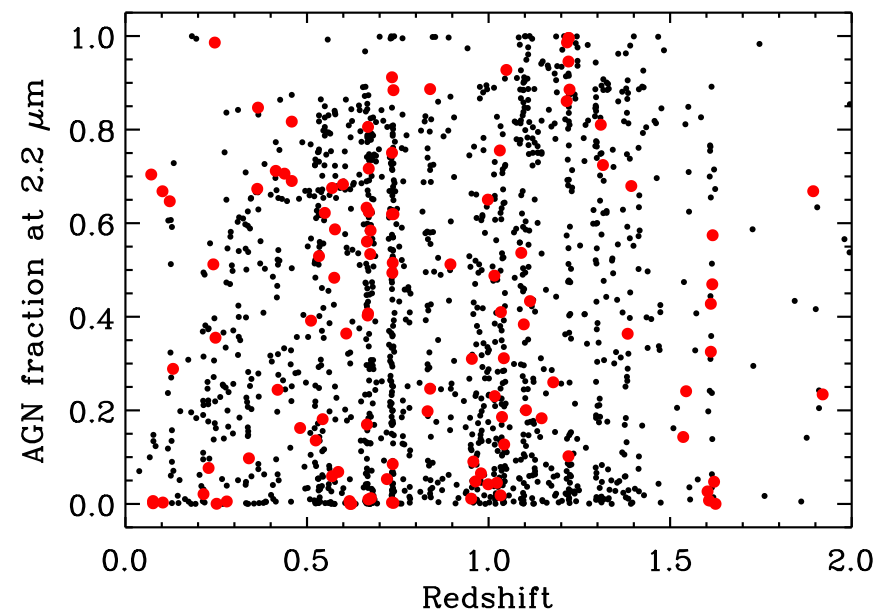
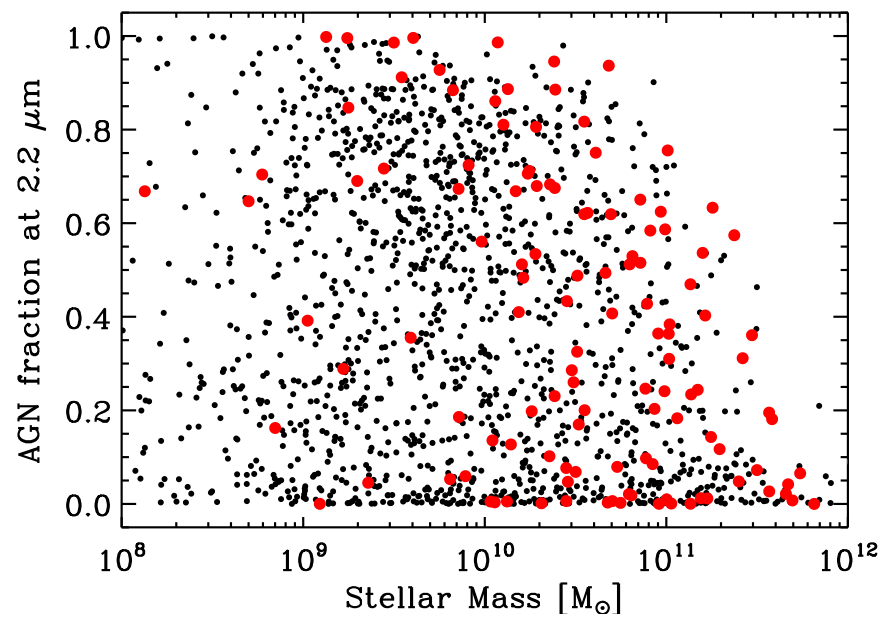
- JWST can trace AGN-growth, host galaxy masses and ages since $z \sim 10$.



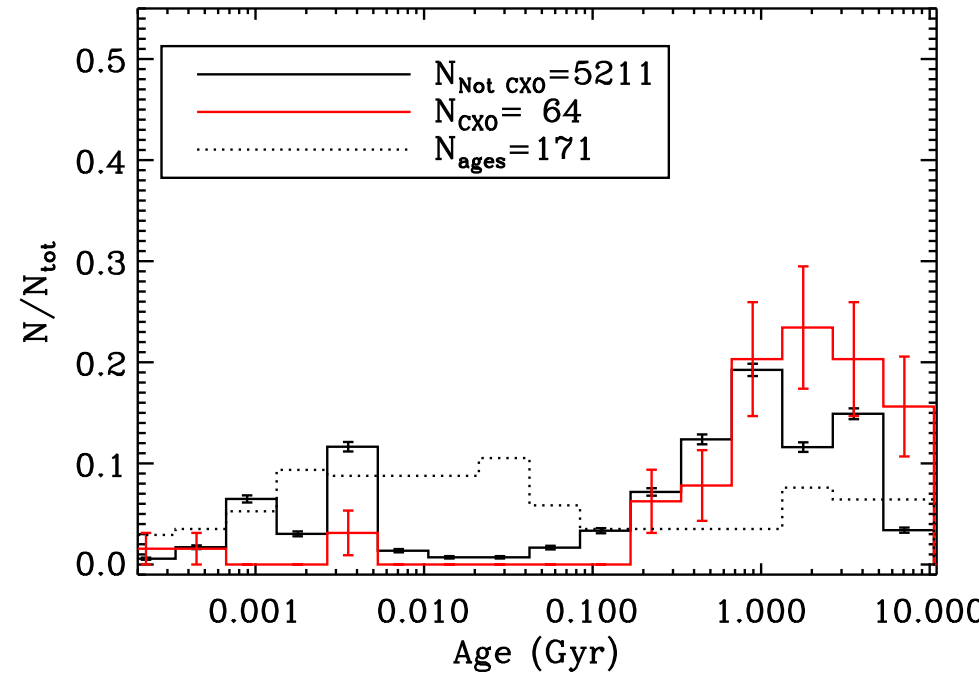
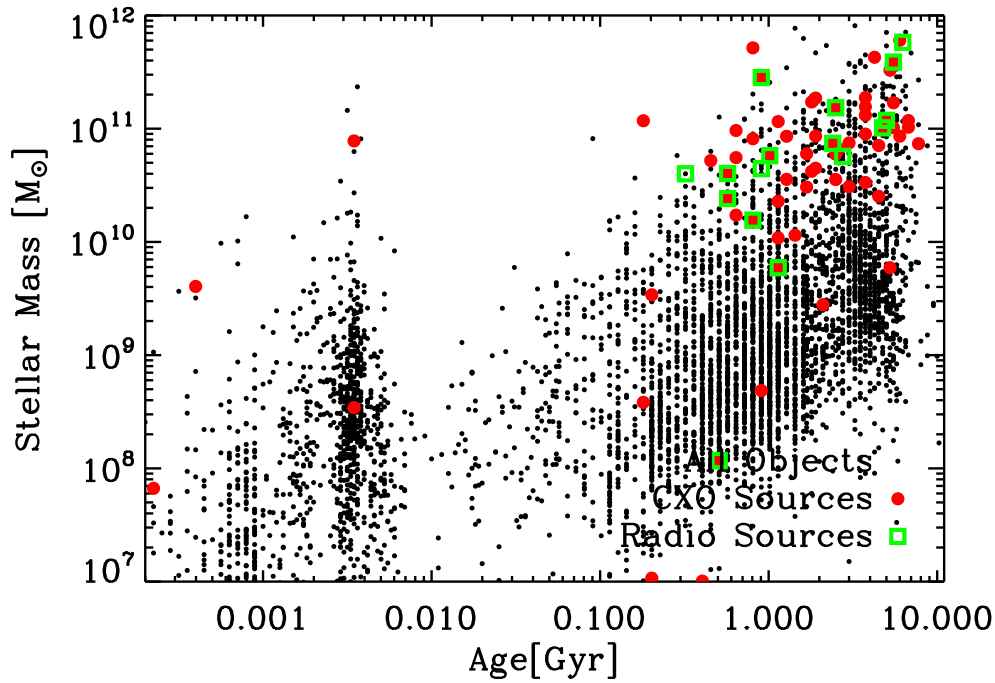
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- Cohen⁺ (2010): AGN fraction vs. Stellar Mass & z : X-ray and field gxy's.
- \Rightarrow Many more with best-fit $f(\text{AGN}) \gtrsim 50\%$ to be detected by IXO or SKA!
- JWST can trace power-law SED-fraction for $M \gtrsim 10^8 M_{\odot}$ and $z \lesssim 10$.



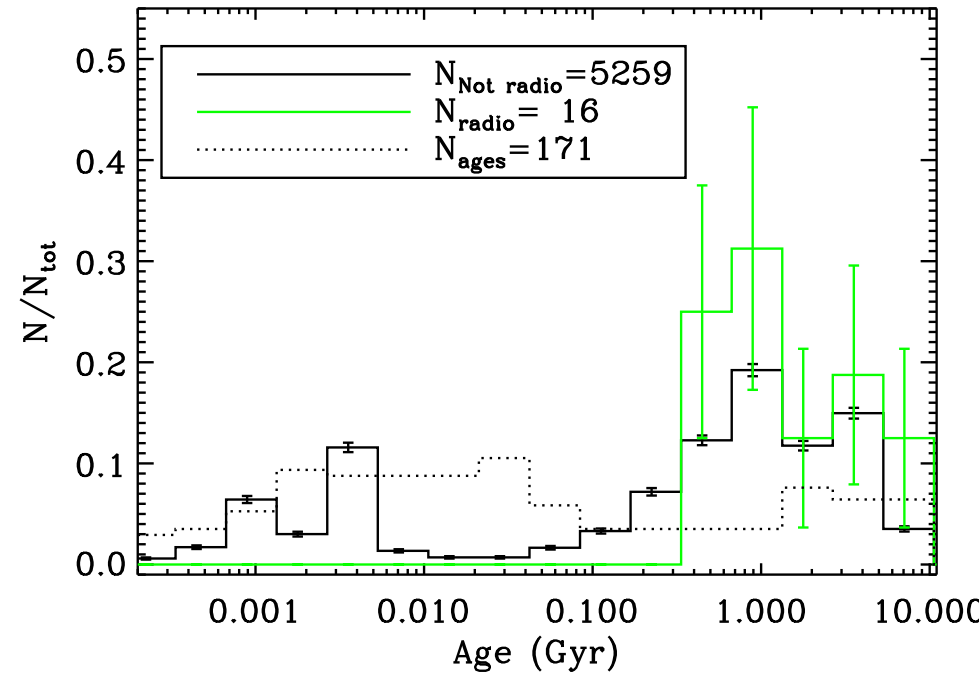
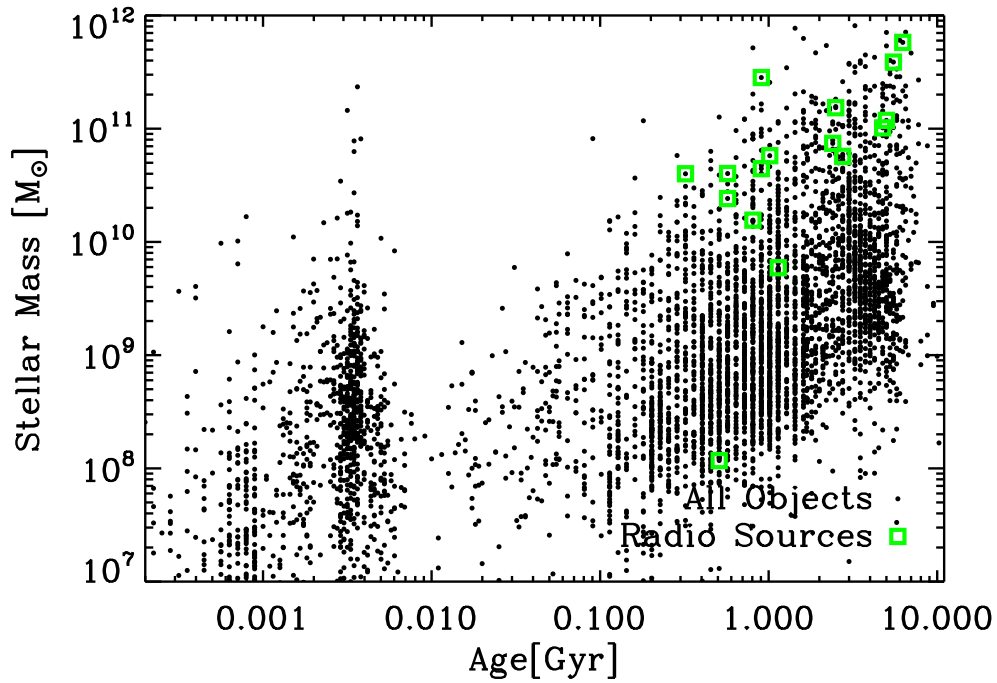
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- X-ray sources reside in galaxies with $M \gtrsim 10^{10} M_{\odot}$, and are older than the field population by $\lesssim 0.5\text{-}1$ Gyr on average.

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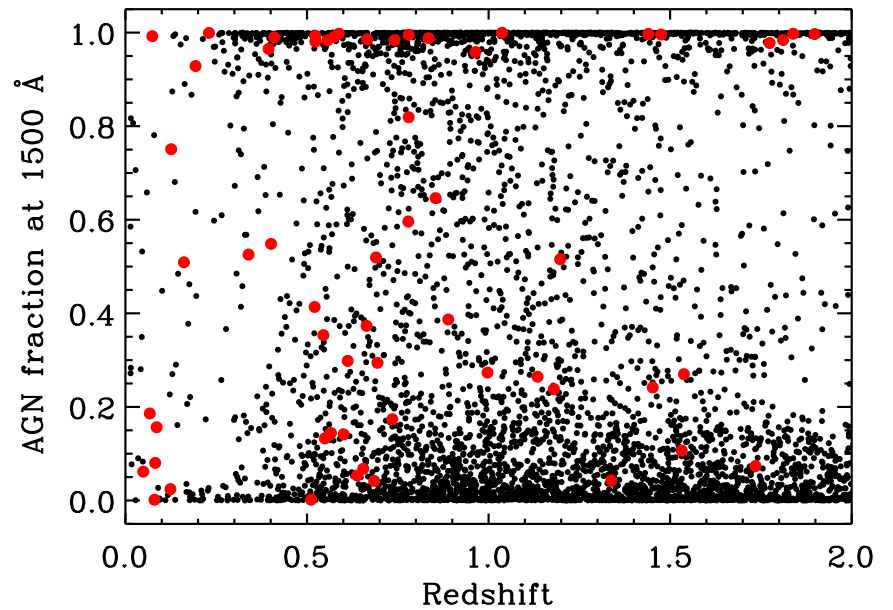
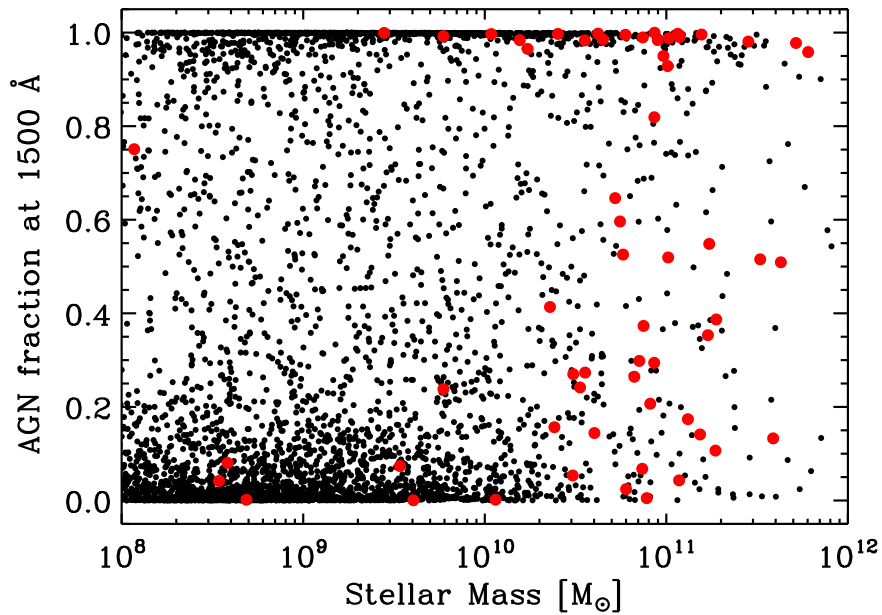
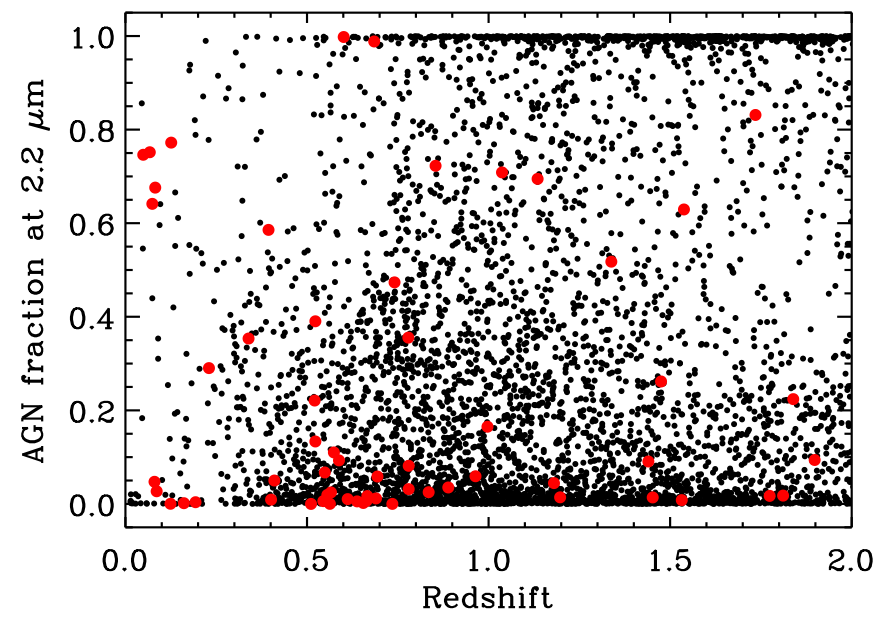
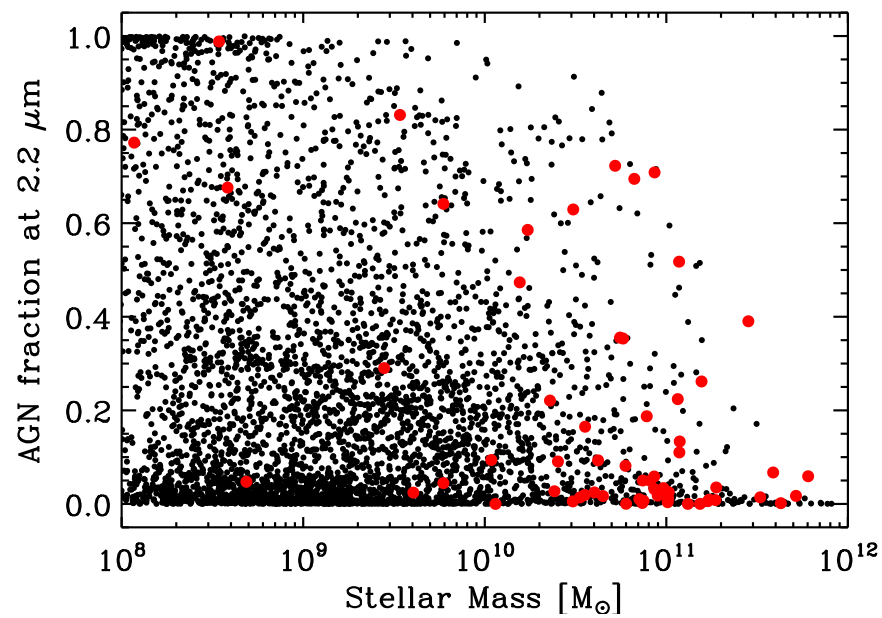
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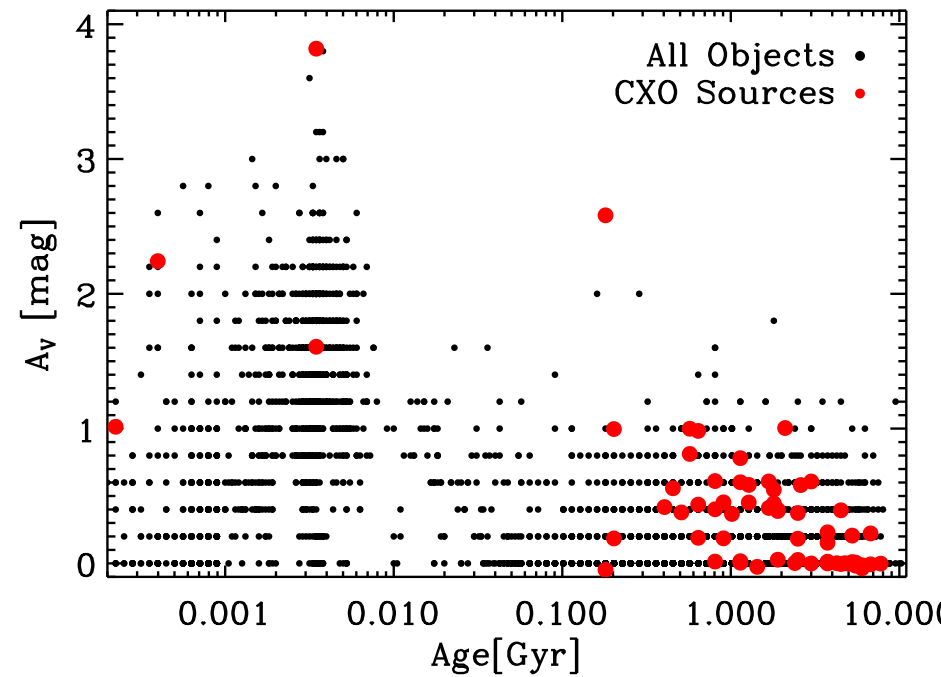
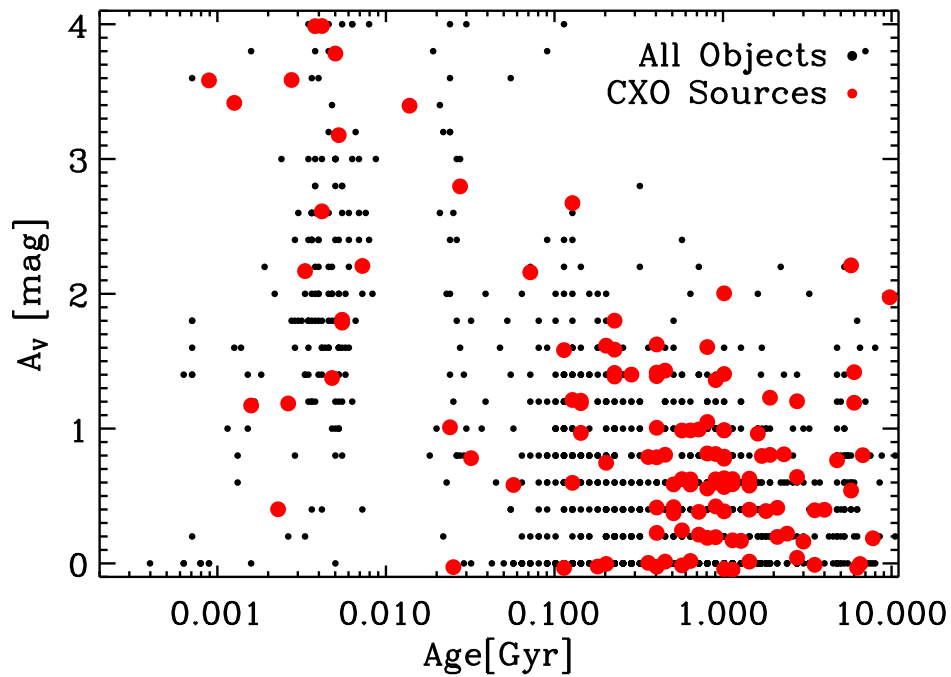
- Radio sources reside in galaxies with $M \gtrsim 10^{10} M_{\odot}$. Not enough statistics yet to say if radio hosts in ERS older than field galaxies.

- JWST+WFC3 can disentangle multiple SED + AGN power-law from 15-band photometry to AB=30 mag for $z \lesssim 10$.

- JWST can trace AGN-growth, host galaxy masses and ages since $z \sim 10$.



- Cohen⁺ (2010): AGN frac vs. Stellar Mass & *spz*: X-ray & field gxys.
 \Rightarrow Many more with best-fit $f(\text{AGN}) \gtrsim 50\%$ to be detected by IXO or SKA!
 ● JWST can trace power-law SED-fraction for $M \gtrsim 10^8 M_{\odot}$ and $z \lesssim 10$.



LEFT: 1549 CDF-S objects with z 's. RIGHT: 7000 CDF-S ERS with spz 's.

Cohen et al. (2010): Best fit extinction A_V distribution: X-ray and field.

- In Hopkins et al. (2006, ApJS, 163, 1) scenario, dust and gas are expelled *after* the starburst peaks and *before* before the AGN becomes visible.
- Older galaxies have less dust after merger/starburst/outflow.
- But the age-metallicity relation may complicate this.

(6) Summary and Conclusions

(1) (Major) Mergers have a redshift distribution similar to that of HUDF field galaxies, but no AGN seen amongst them.

(2) Variable objects have a redshift distribution similar to that of HUDF field galaxies, and likely trace brief(!) episodes of SMBH growth.

- There is very little overlap between (1) and (2): HUDF mergers likely preceded visible weak-AGN variability.

(3) Epoch dependent density of major mergers may precede peak in X-ray selected AGN $\rho(z)$, but by no more than 1–2 Gyr (circumstantial).

(4) Radio and X-ray selected galaxies are — at $z \simeq 0.5–2$ — on average 0.5–1 Gyr older than the typical FBG or LBG age of 0.1–0.2 Gyr.

(5) AGN growth likely stays in pace with Galaxy Assembly, but Radio &/or X-ray source appear $\lesssim 1$ Gyr after merger/starburst.

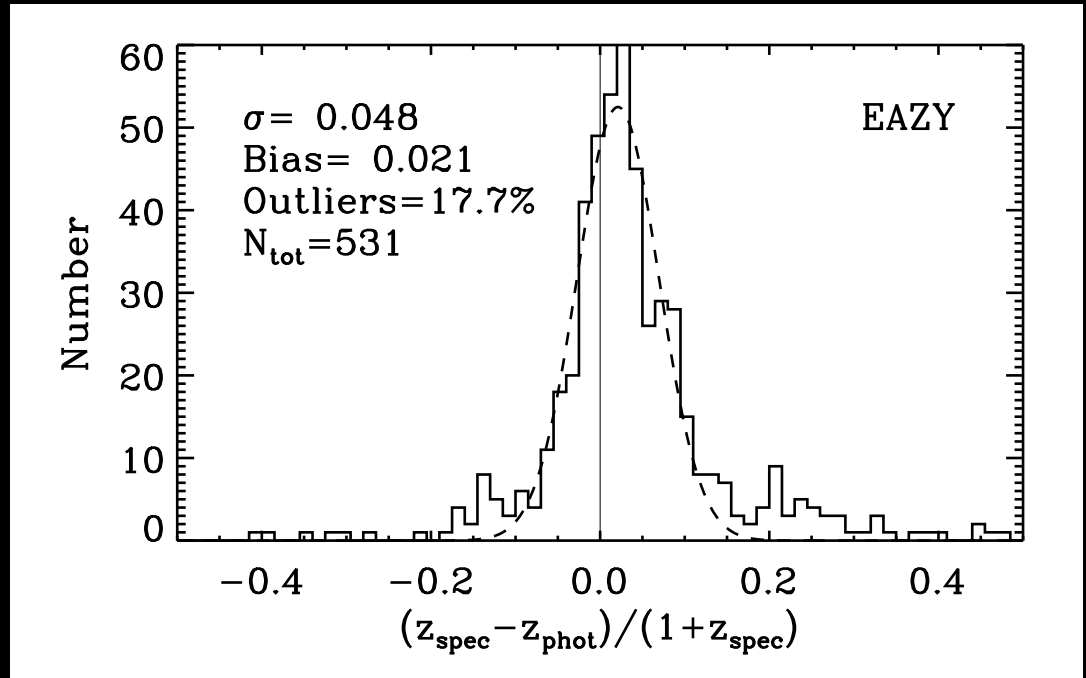
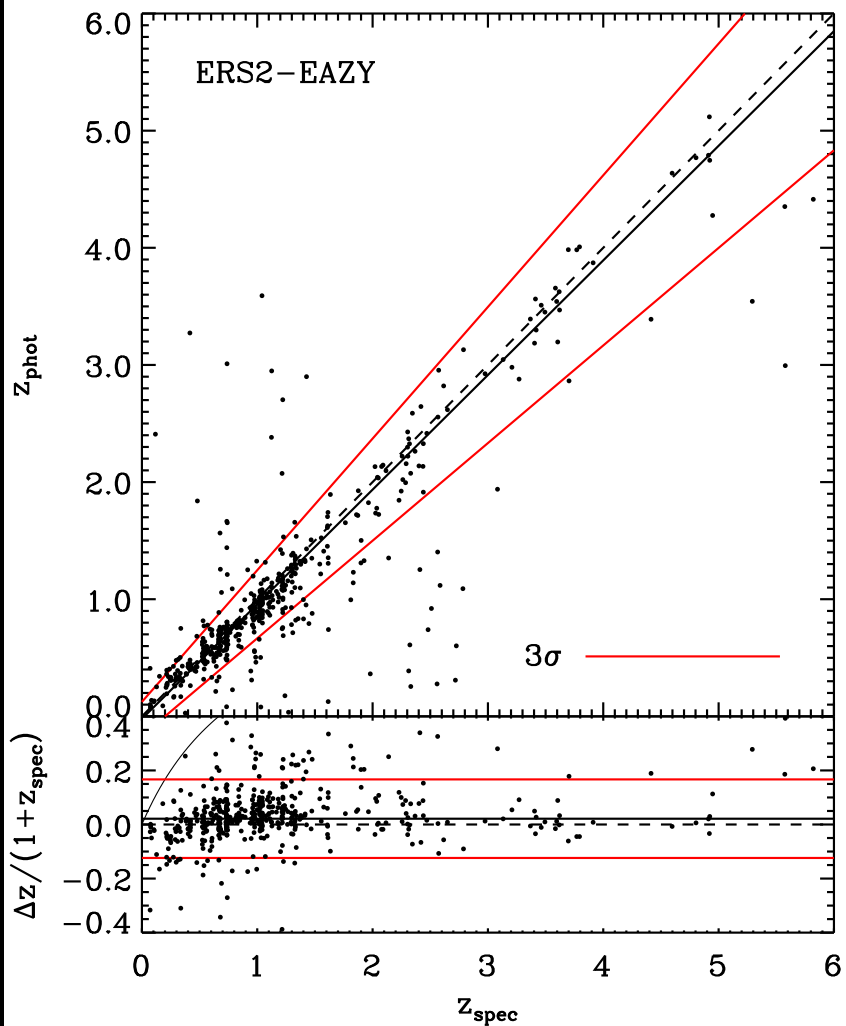
- JWST can measure this in great detail to $AB \lesssim 31$ mag from 0.7–5.0 μm , tracing galaxy assembly and AGN/SMBH-growth since $z \lesssim 10–15$.

SPARE CHARTS



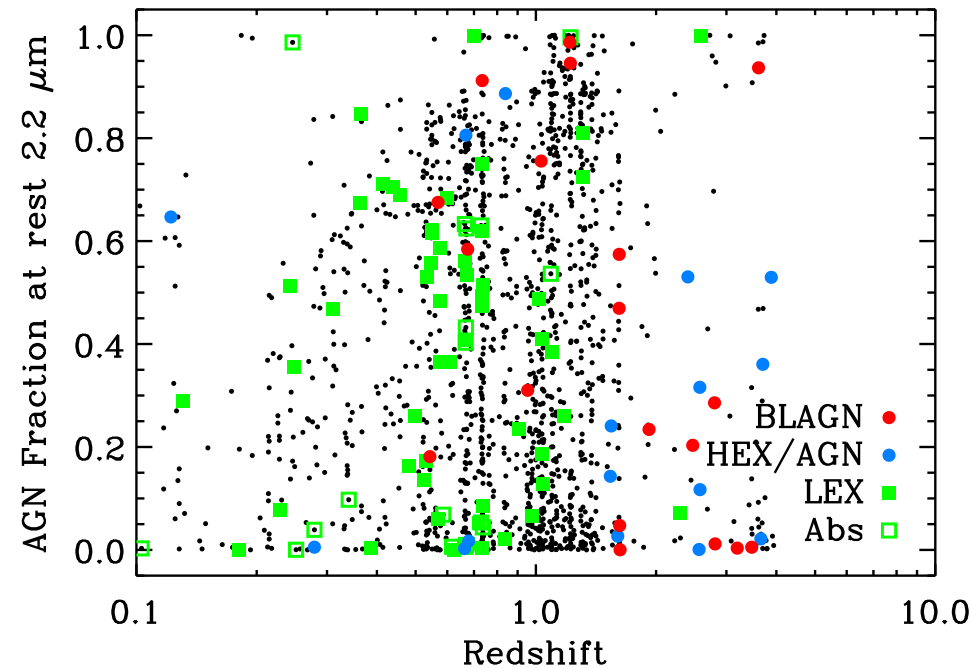
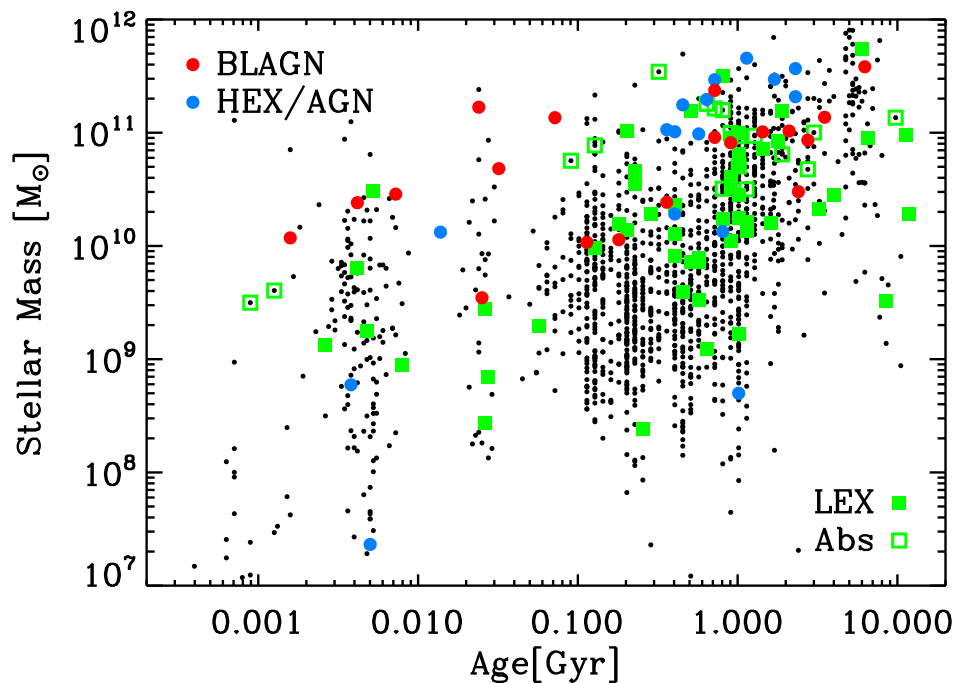
"For God's sake, Edwards. Put the laser pointer away."

The danger of having Quasar-like devices too close to home ...



WFC3 ERS 10-band redshift estimates accurate for $AB \lesssim 27$ mag to $\sim 4\%$, especially at $1 \lesssim z \lesssim 2$, with small systematics (Cohen et al. 2010).

- JWST can get accurate photo-z's to $AB \lesssim 31$ mag for at $z \simeq 0.5-15$.



Cohen et al. (2010): At all ages, the most massive hosts are QSO-1/2's (based on AGN lines in *optical spectra* by Szokoly et al. 2004):

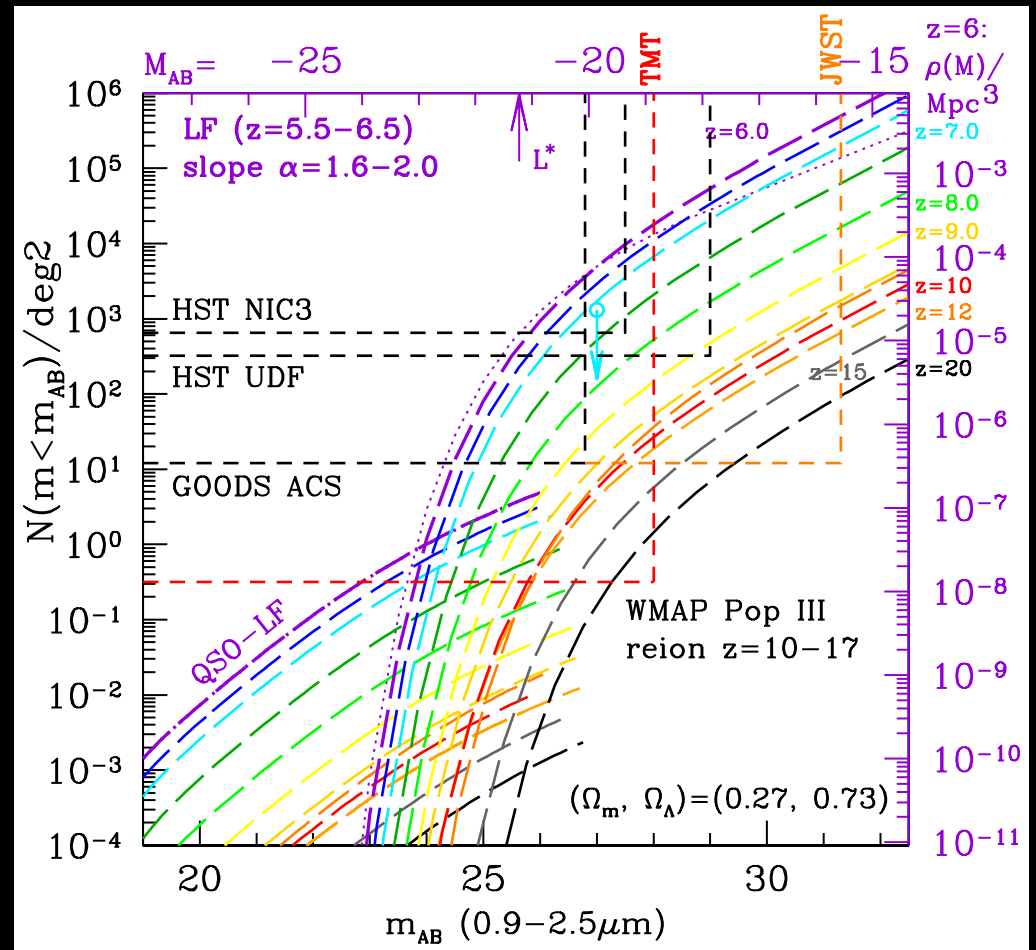
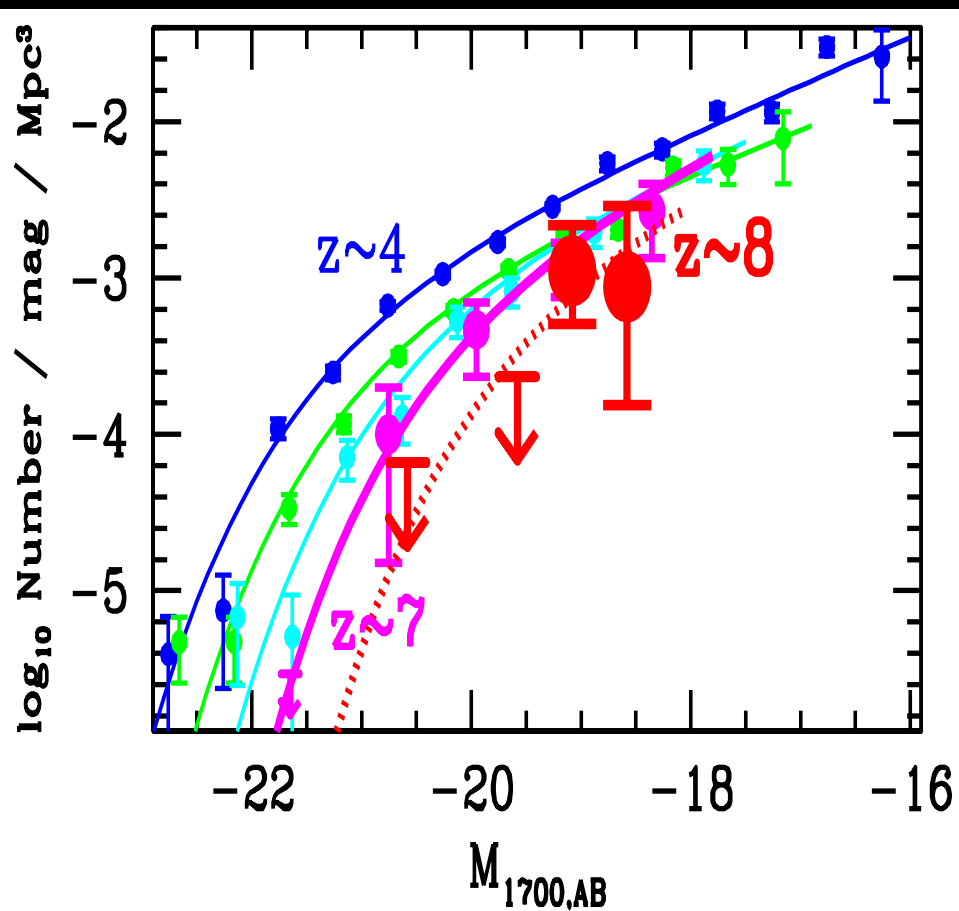
- This illustrates the well known L_X - L_{opt} correlation.

All optical AGN types: emission lines and absorption features.

Most $\gtrsim 0.5$ – 1 Gyr SEDs do not show AGN signatures in optical spectra.

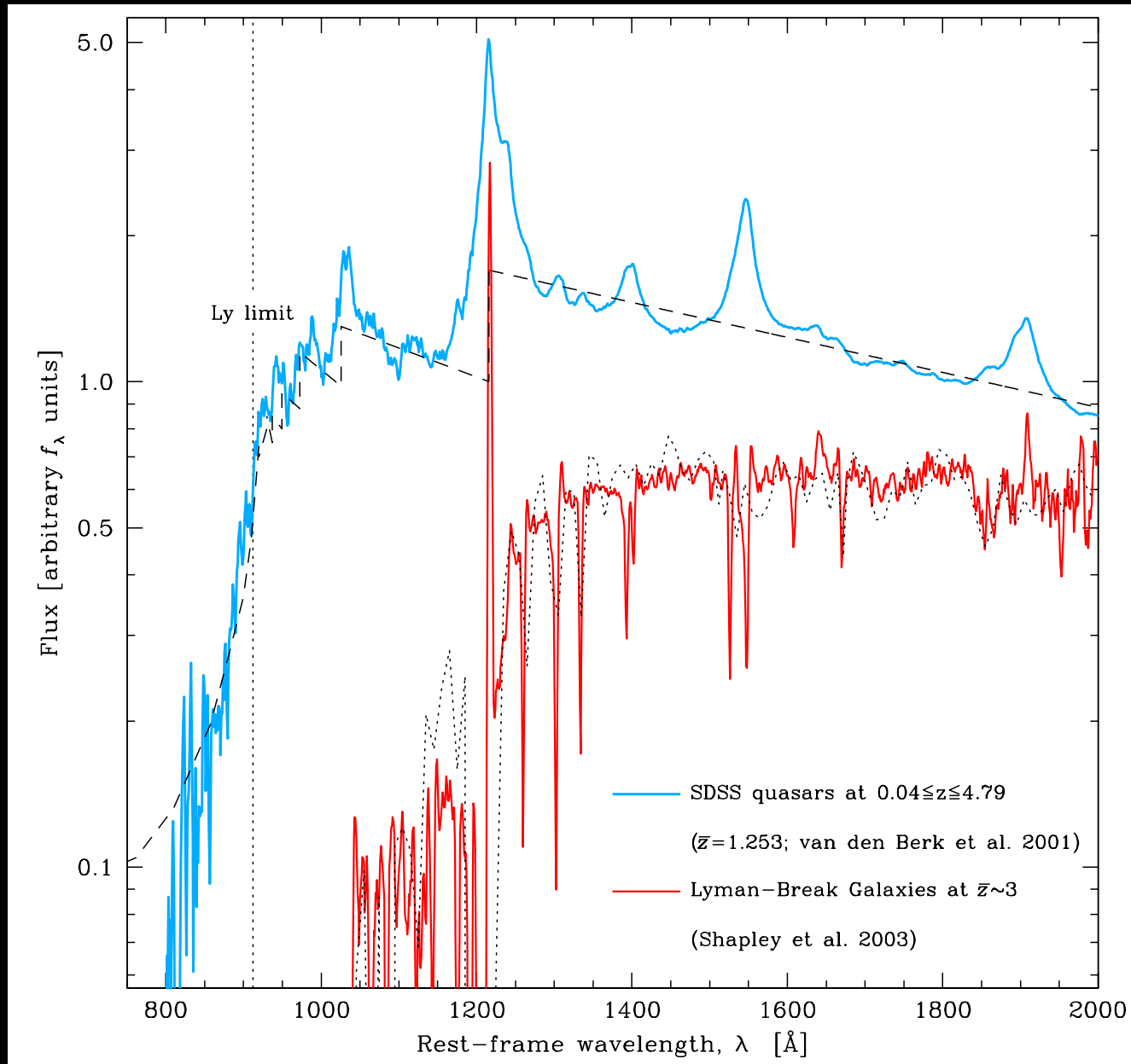
- For majority of AGN-1's: $\lesssim 50\%$ of $2 \mu\text{m}$ -flux comes from the AGN !?

Many more with best-fit $f(\text{AGN}) \gtrsim 50\%$ to be detected by IXO or SKA!



- Objects at $z \gtrsim 9$ are rare (Bouwens⁺ 2010, Yan⁺ 2010), since volume element is small and JWST samples brighter part of LF. JWST needs its sensitivity/aperture (A), field-of-view (Ω), and λ -range (0.7-29 μm).
- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.
- To study co-evolution of SMBH-growth and proto-bulge assembly for $z \lesssim 10-15$ requires new AGN finding techniques for JWST.

Caveat: Can the Hard-UV of weak AGN outshine Dwarf Galaxies?

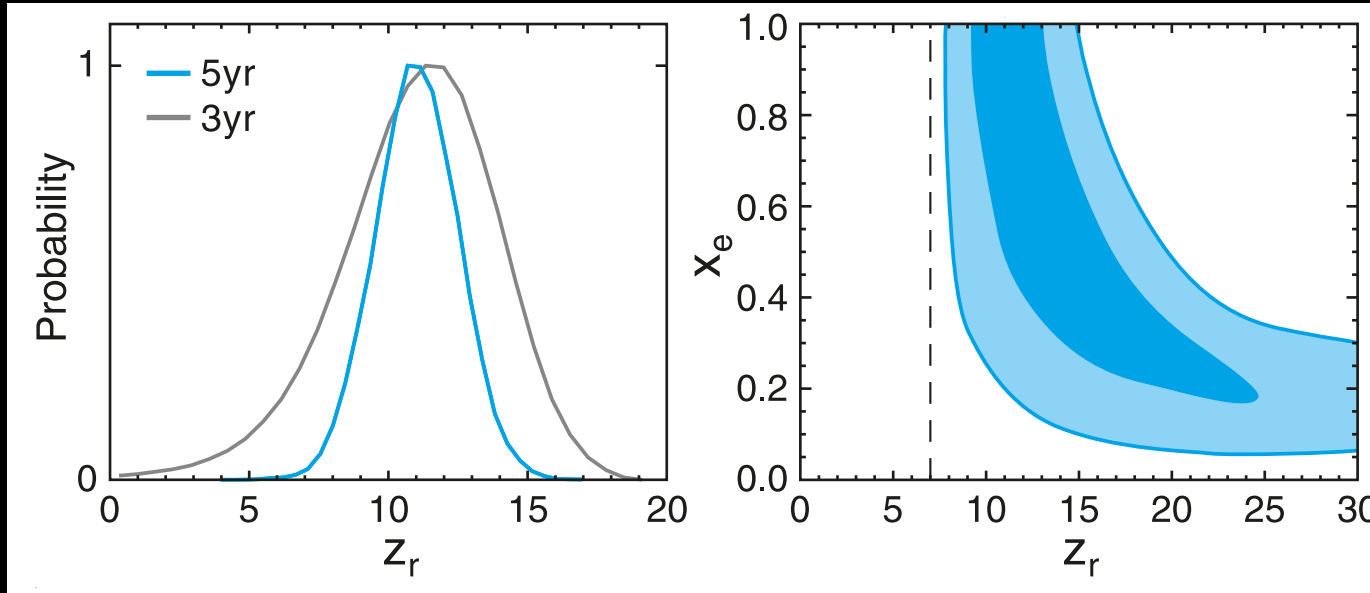


- In principle, the hard-UV of QSO's and weak AGN can outdo the young SED's of LBG's or dwarf galaxies, but likely by no more than $\gtrsim 1$ dex.

Implications of the (2010) 7-year WMAP results for JWST science:

HST/WFC3 $z \lesssim 7-9$ ←

→ JWST $z \simeq 8-25$



The year-7 WMAP data provided much better foreground removal (Dunkley et al. 2009; Komatsu et al. 2009, 2010; astro-ph/1001.4538)

⇒ First Light & Reionization occurred between these extremes:

- (1) Instantaneous at $z \simeq 10.4 \pm 1.2$ ($\tau = 0.087 \pm 0.014$), or, MORE LIKELY:
- (2) Inhomogeneous & drawn out: starting at $z \gtrsim 20$, peaking at $z \simeq 11$, ending at $z \simeq 7$. The implications for HST and JWST are:

- HST/ACS has covered $z \lesssim 6$, and WFC3 is now covering $z \lesssim 7-9$.

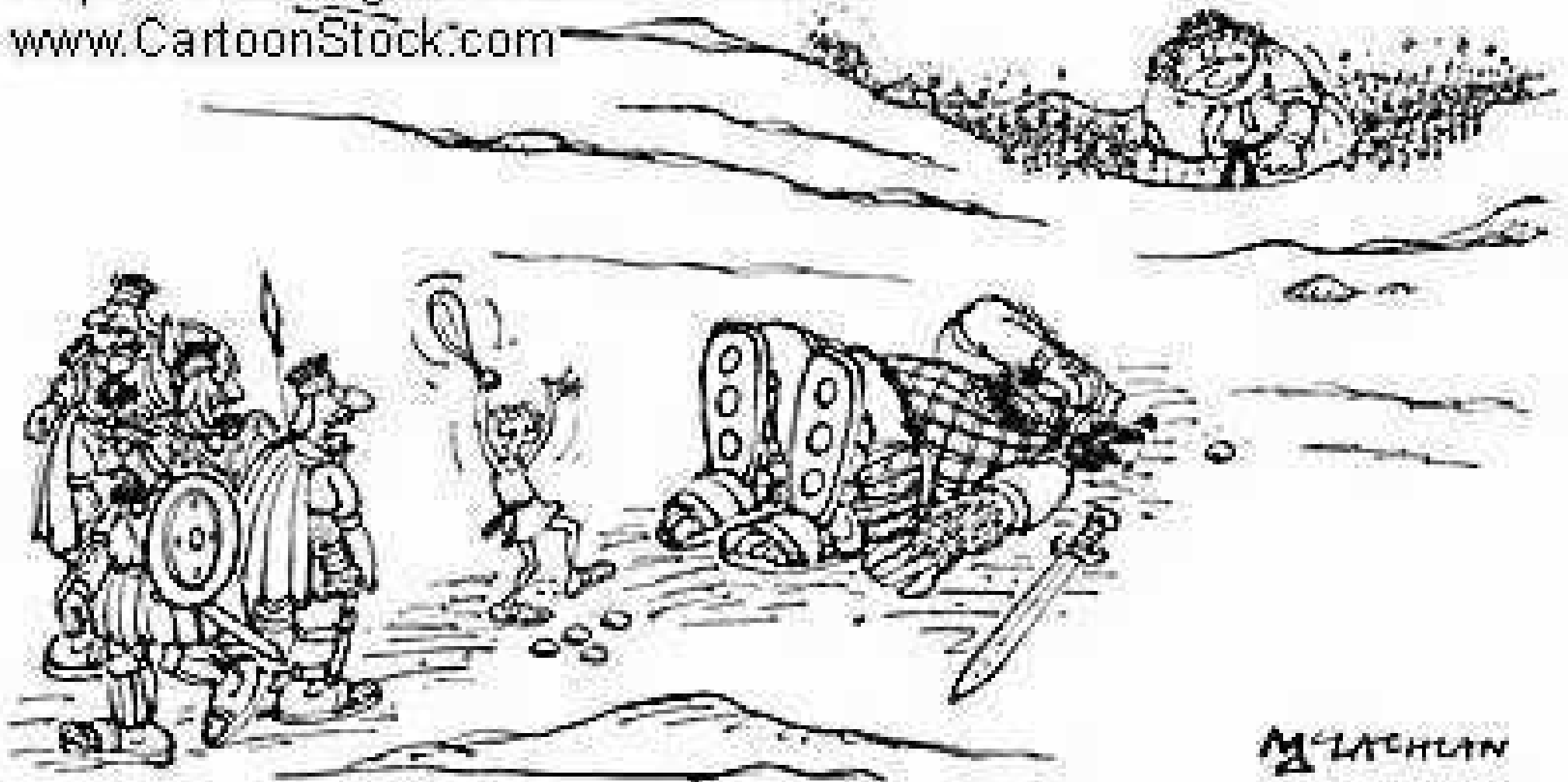
- For First Light & Reionization, JWST must sample $z \simeq 8$ to $z \simeq 15-20$.

⇒ JWST must cover $\lambda = 0.7-29 \mu\text{m}$, with its diffraction limit at $2.0 \mu\text{m}$.



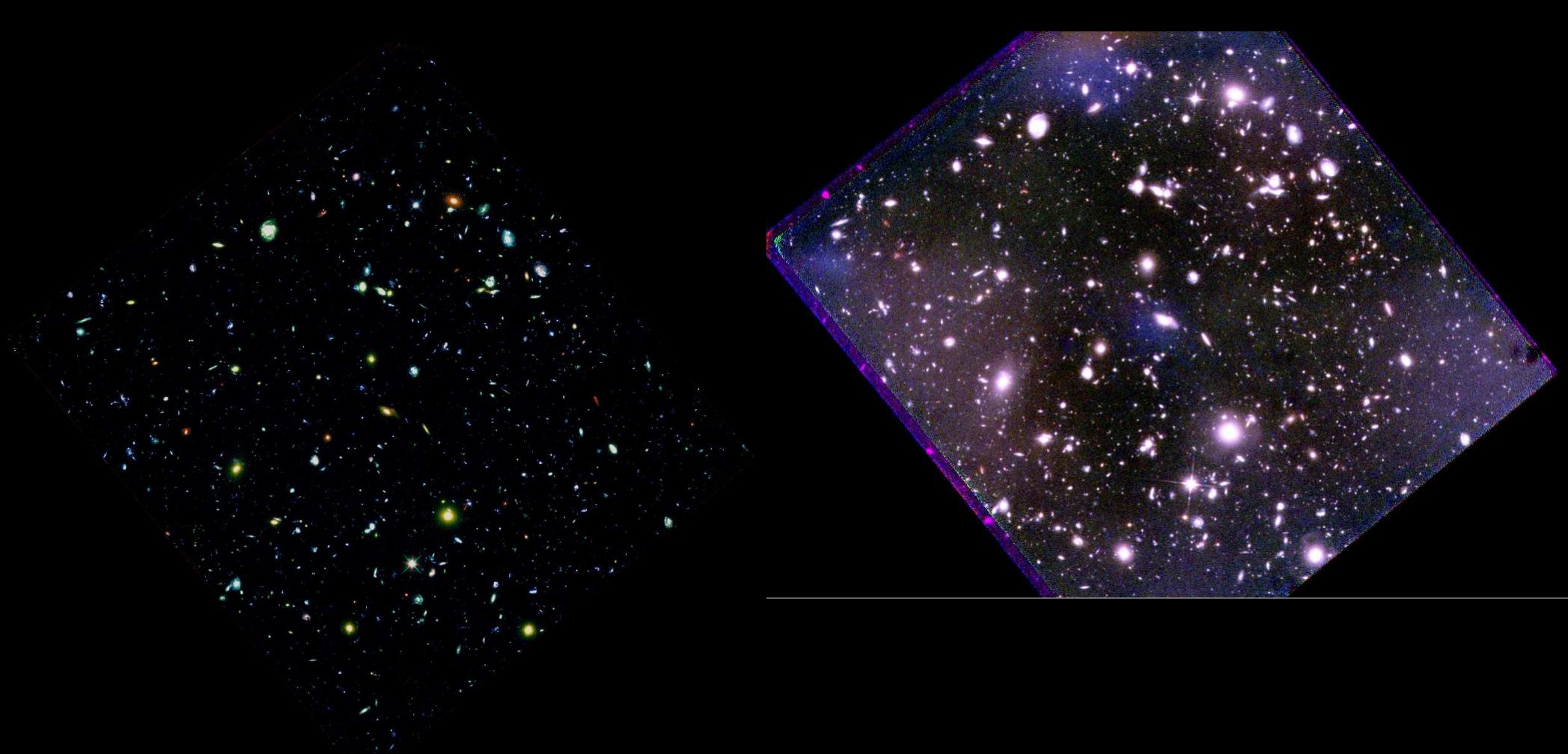
At the end of H-reionization, dwarfs had beaten the Giants, but ...

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"You've done it now, David - Here comes his mother."

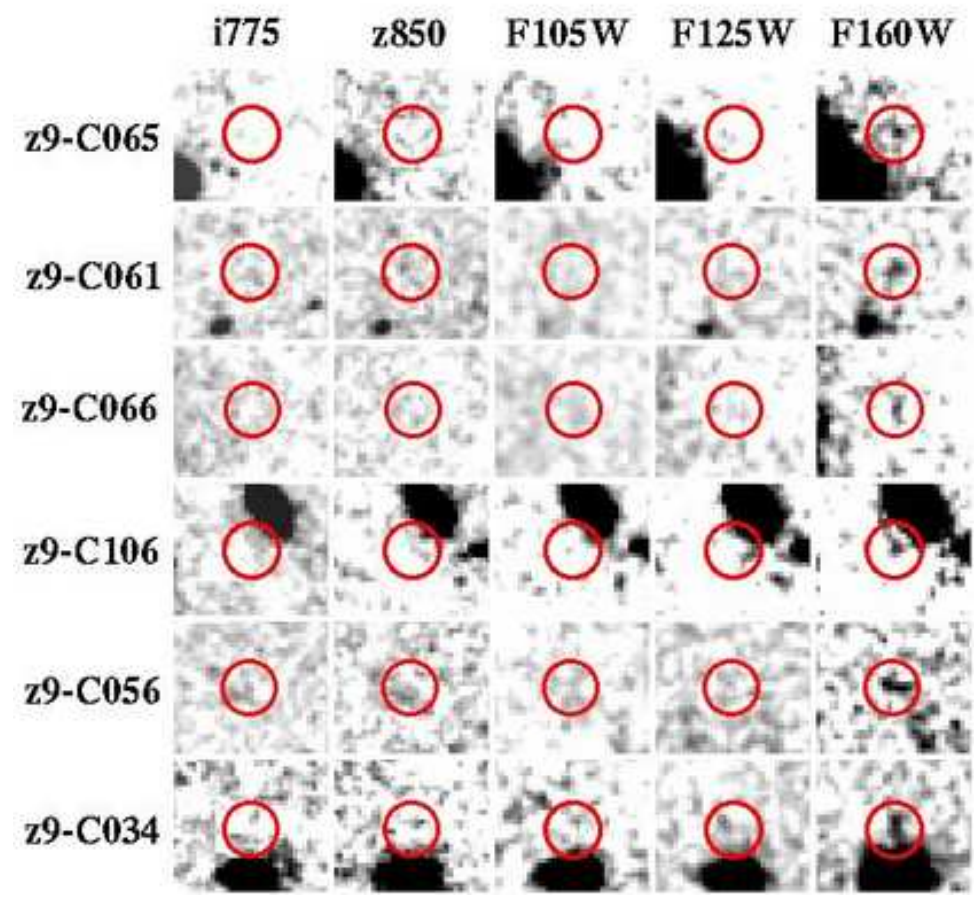
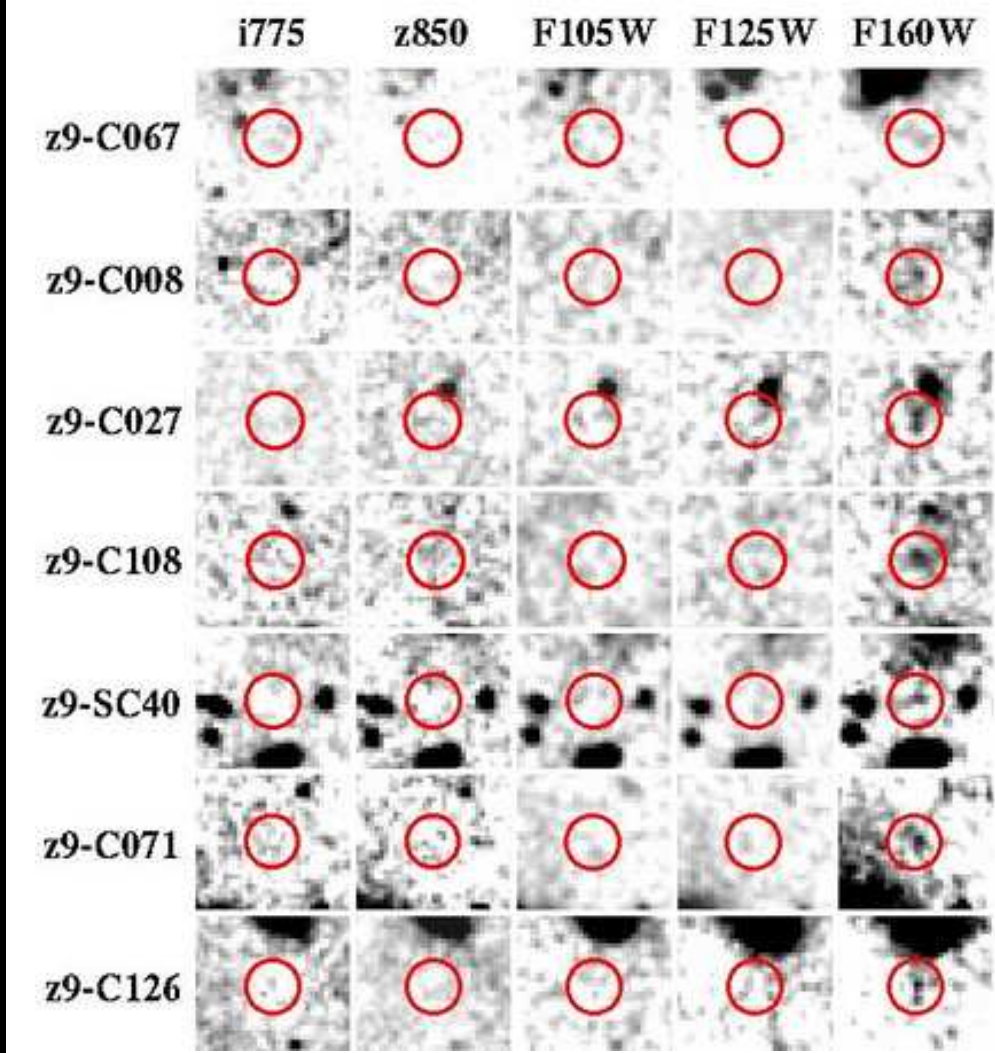
What comes around, goes around ...



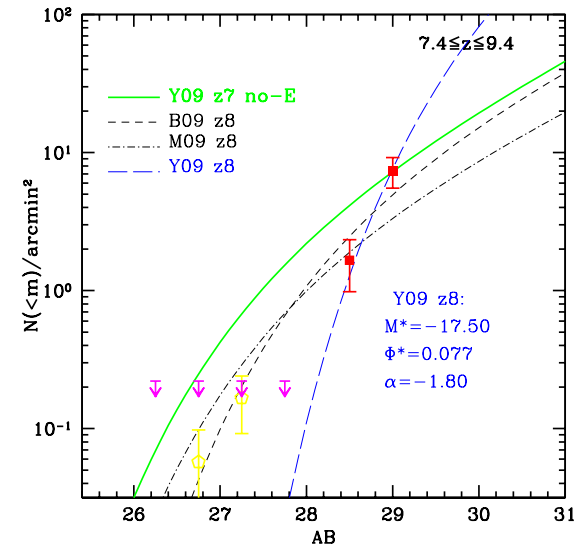
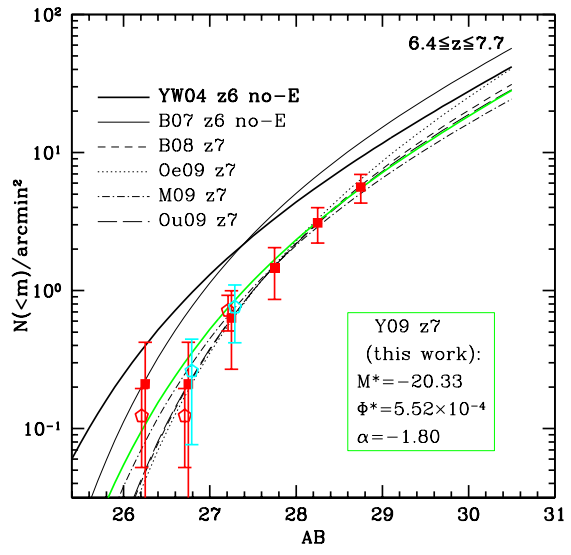
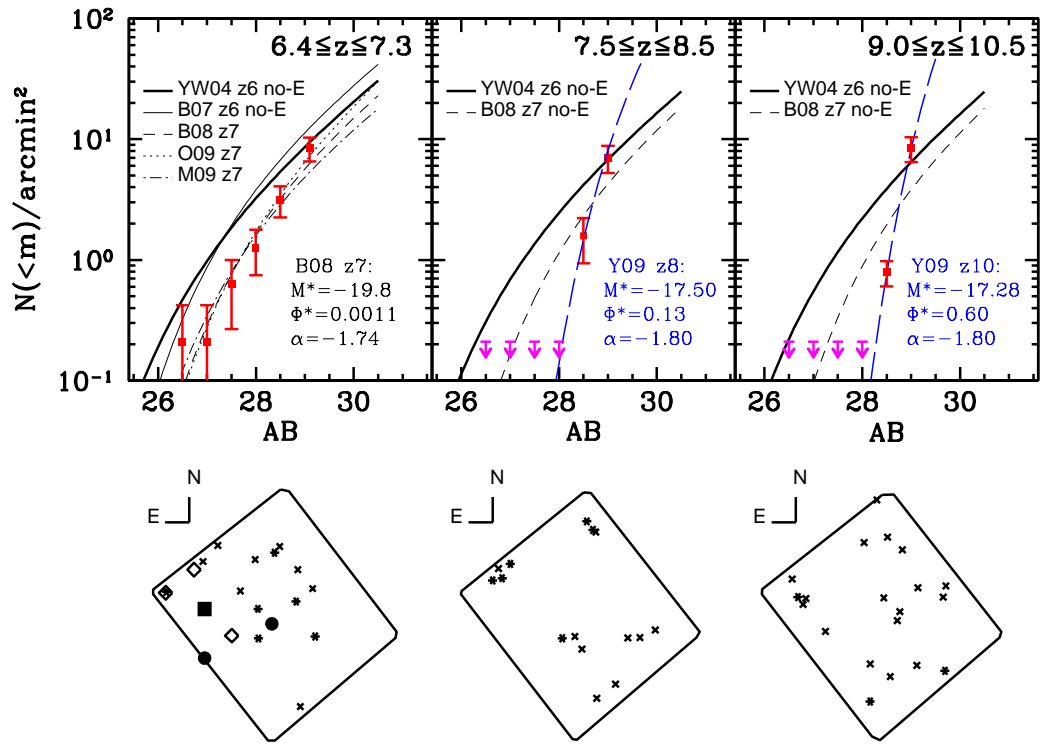
(Left) HST/WFC3 IR-mosaic in YJH in the HUDF: Bouwens et al (2010), Yan et al. (2009; astro-ph/0910.0077).

(Right) Same WFC3 IR-mosaic, but stretched to $\lesssim 10^{-3}$ of Zodi sky!!

- The CLOSED-TUBE HST has residual low-level systematics: imperfect removal of detector artifacts, flat-fielding errors, and/or faint straylight.
- The open JWST architecture needs perfect baffling and rogue path mitigation to do ultradeep JWST fields (JUDF's) to 10^{-4} of sky.

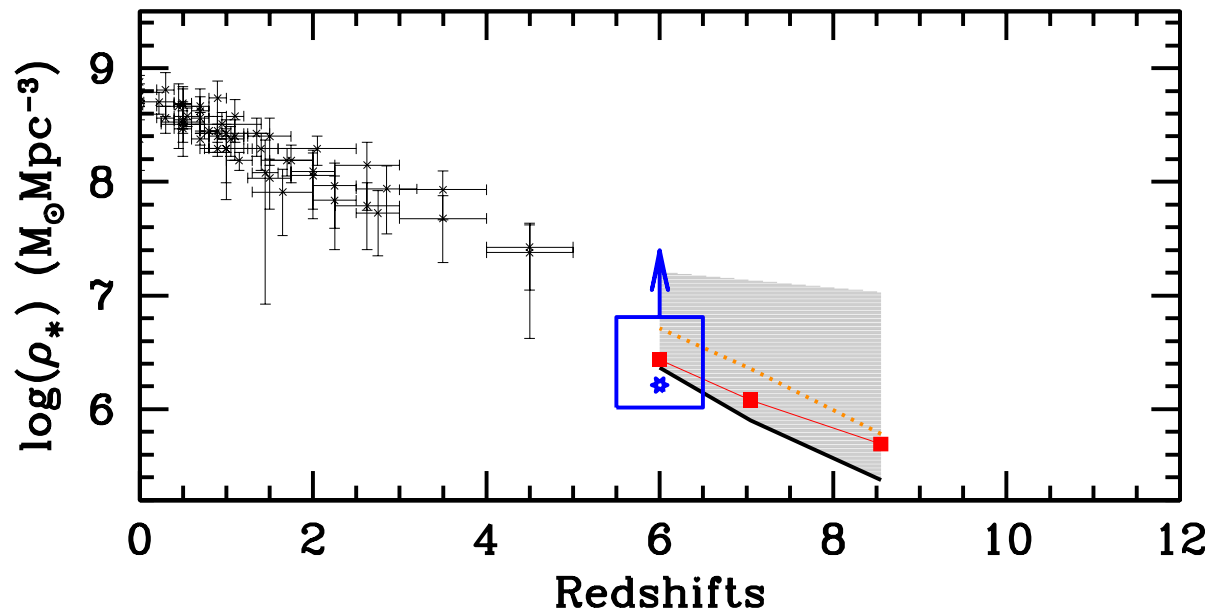
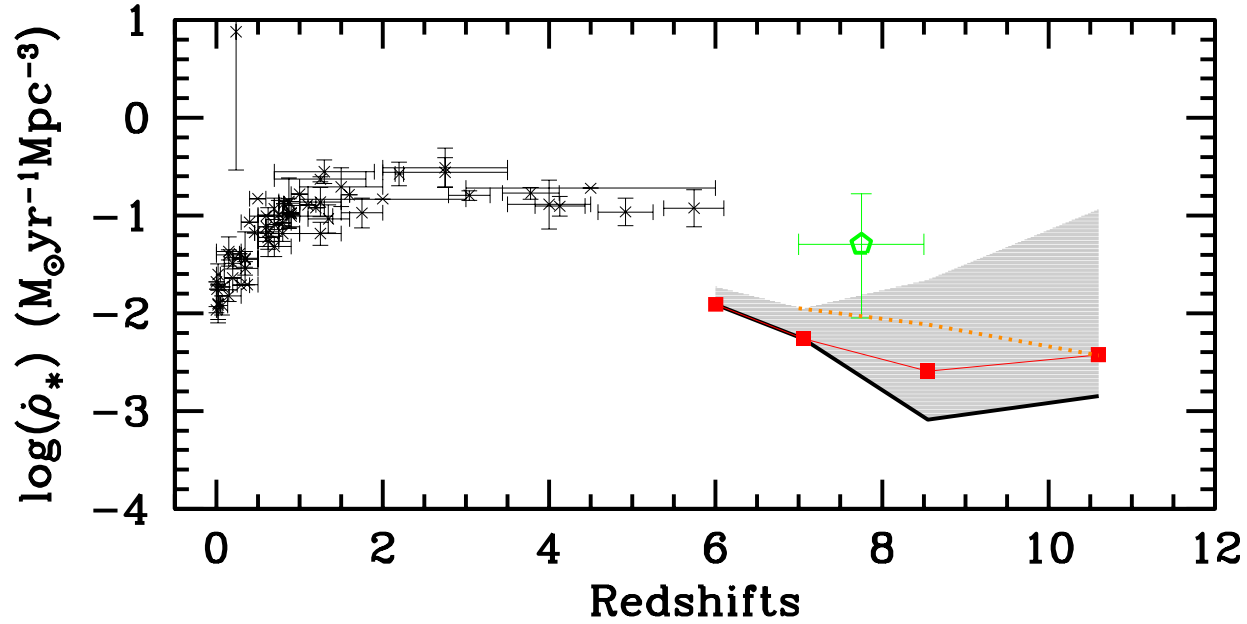


- Our simulations show that $\sim 50\%$ of the J-drops close to bright galaxies are real (unlike Bouwens 2010), see Yan et al. 2010 (astro.0910.0077).
- Assume only 33% of J-drops are real *and* at $z \gtrsim 9$. Together with the HUDF and ERS upper limits to $AB \lesssim 28$ mag, the $z \sim 9$ LF is still steep!
- Need JWST to measure $z \gtrsim 9$ LF, and see if it's fundamentally different from the $z \lesssim 8$ LFs. Does a pop-III driven IMF cause a power-law LF?

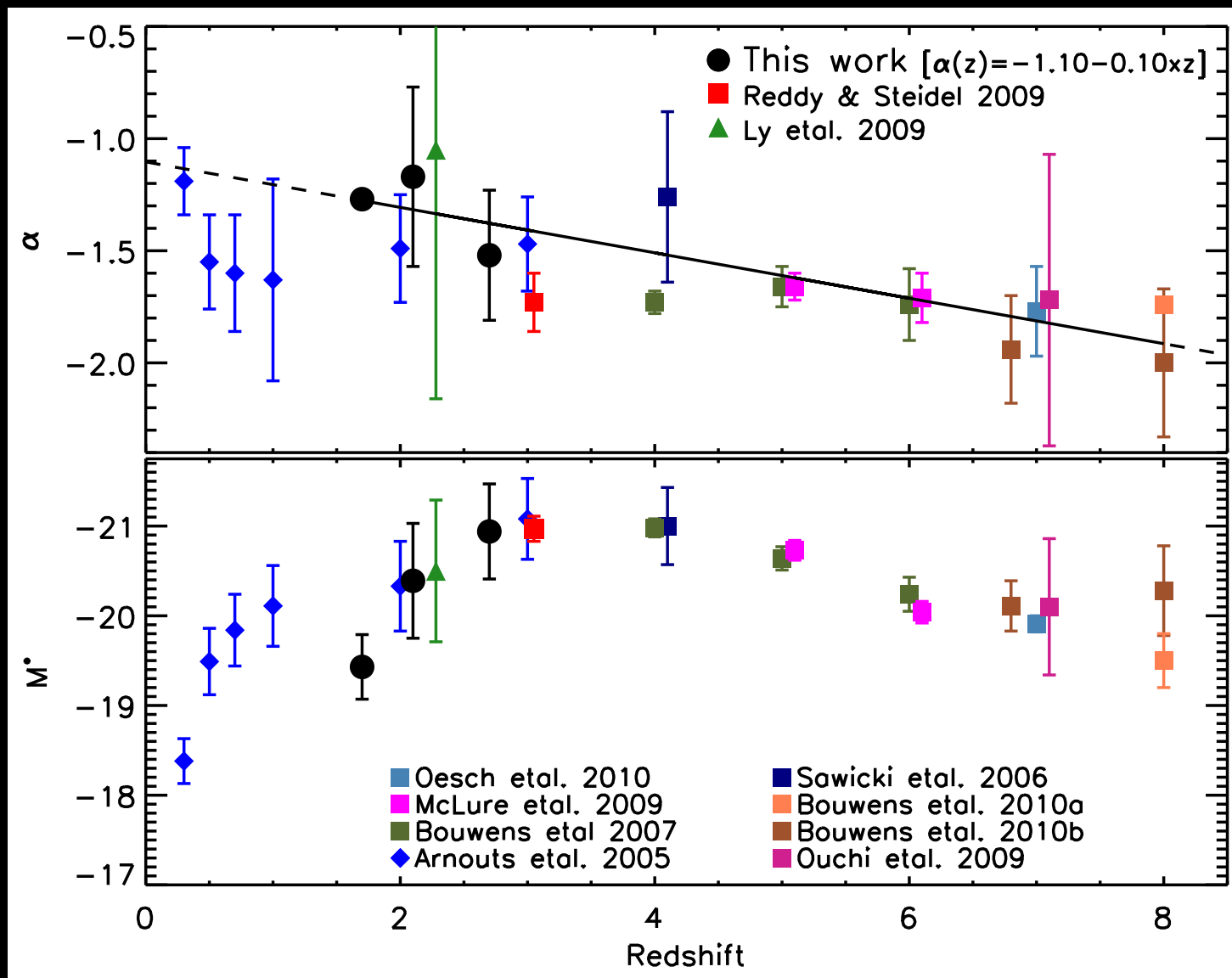


Update of Yan et al. 2009 (astro.0910.0077) HUDF with WFC3 ERS data:

- z=7 LF more firm (see Bouwens), z=8 LF refined, z=9.5 UL's still stand.

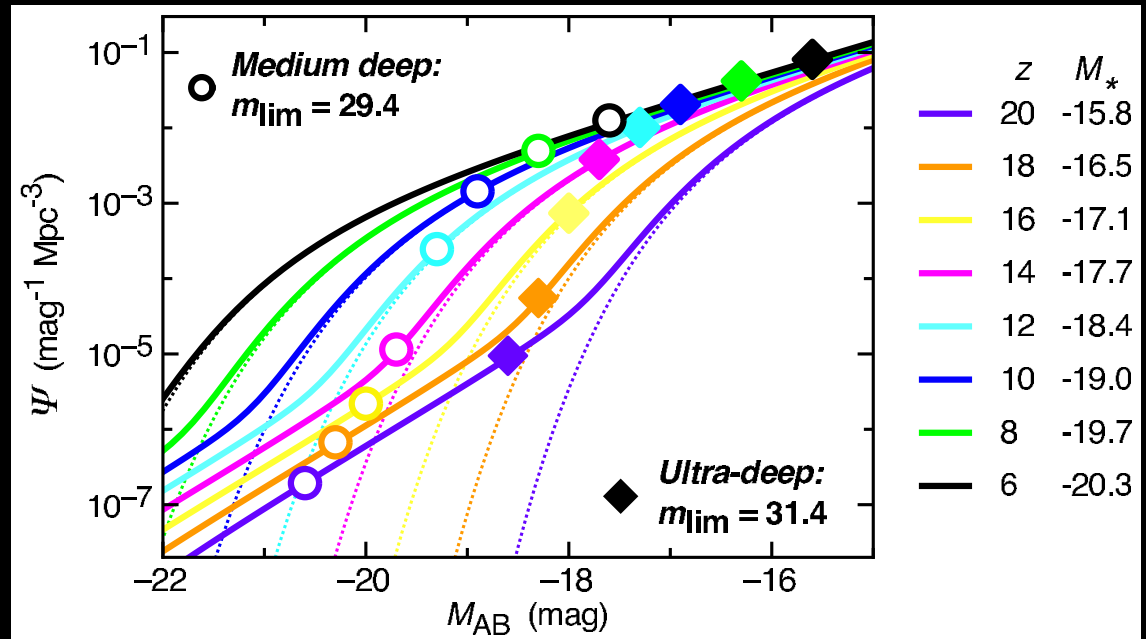
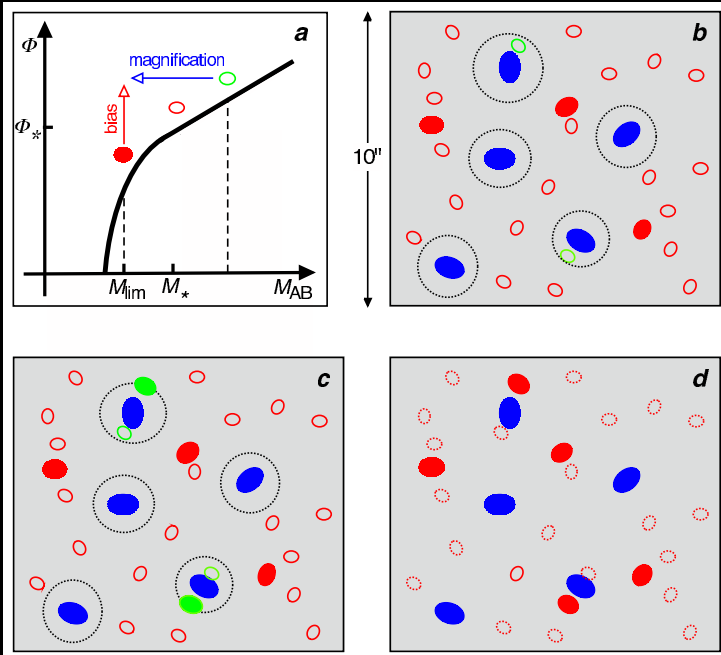
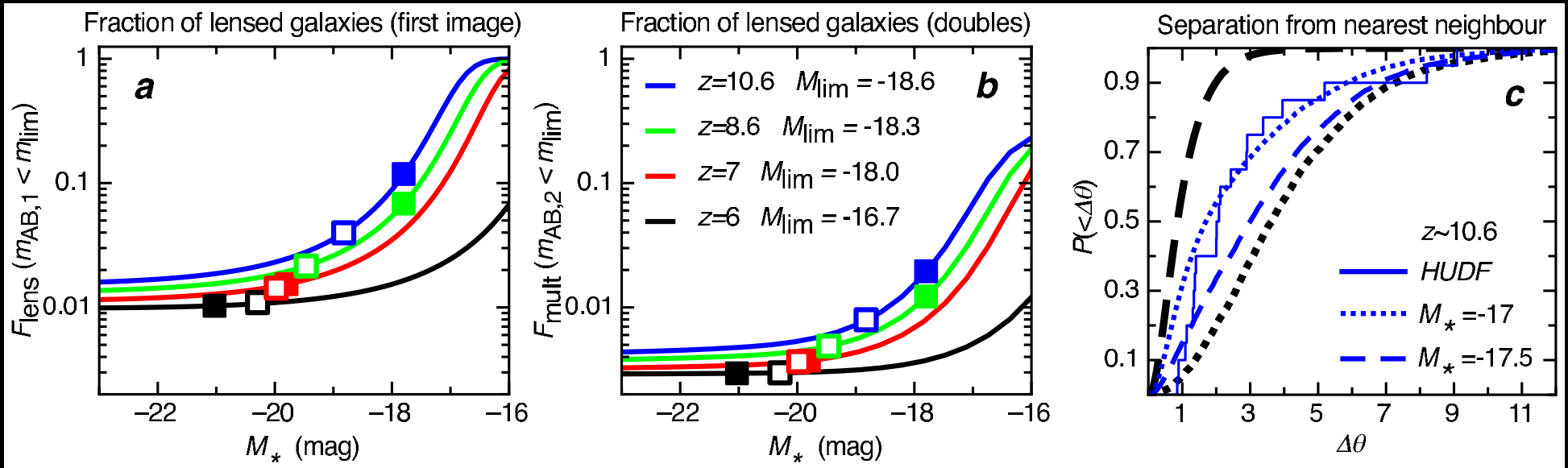


- The current WFC3 uncertainties on J-drops are large enough that at $z \gtrsim 8$, a wide range of possibilities is allowed (Yan et al. 2010; astro.0910.0077).
- Need JWST to fully measure the LF and SFR for $8 \lesssim z \lesssim 15$.



Measured faint-end LF slope evolution (top) and characteristic luminosity evolution (bottom) from Hathi et al. 2010, ApJ, 720, 1708 (arXiv:1004.5141v2).

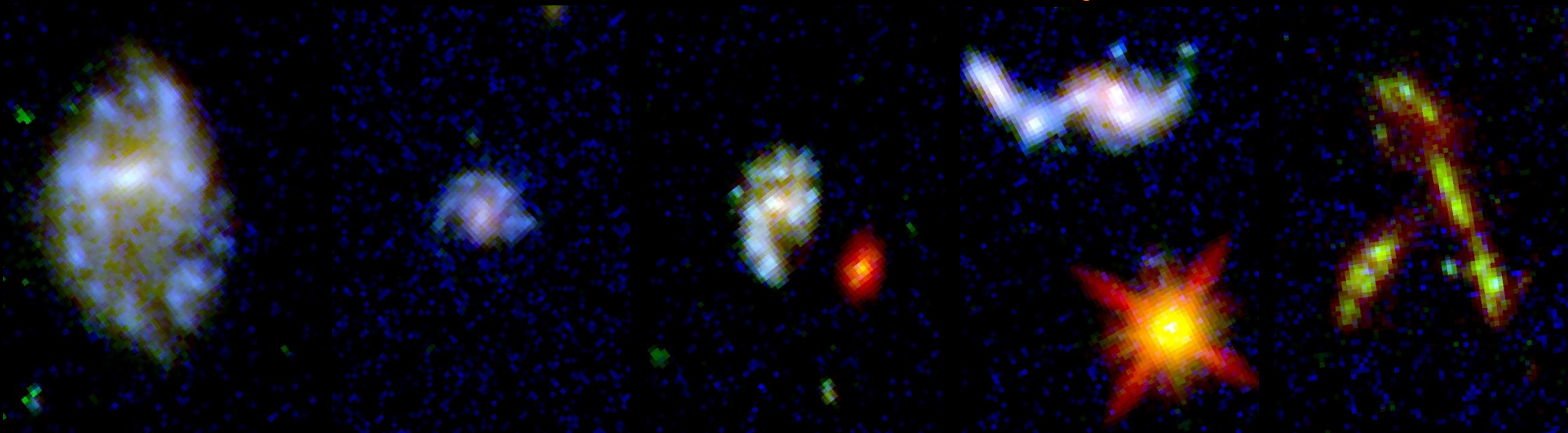
- In the JWST regime at $z \gtrsim 8$, expect faint-end LF slope $\alpha \simeq 2.0$!
- In the JWST regime at $z \gtrsim 8$, expect characteristic luminosity $M^* \gtrsim -19$!



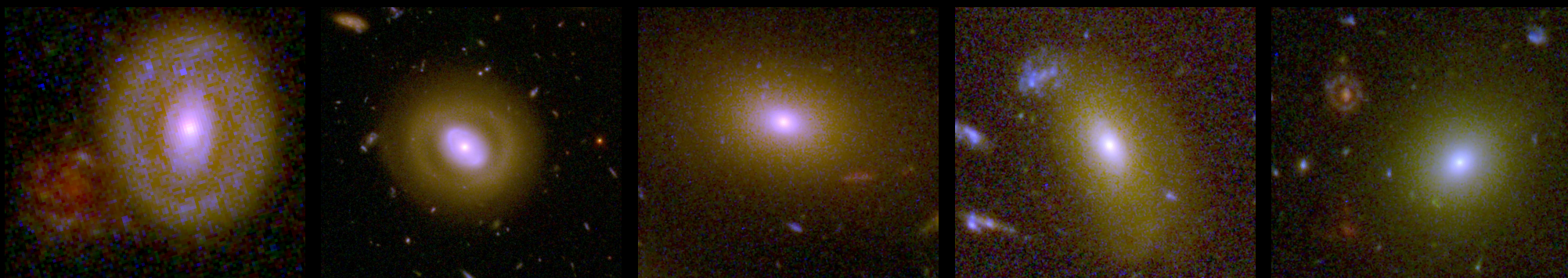
Wyithe et al. (2010, Nature, in press): With a steep faint-end LF-slope $\alpha \gtrsim 2$, and a characteristic faint $M^* \gtrsim -19$ mag, foreground galaxies (at $z \simeq 1-2$) may cause significant boosting by gravitational lensing at $z \gtrsim 8-10$.

● This could change the landscape for JWST observing strategies.

Some science results of the Wide Field Camera Early Release Science data



Galaxy structure at the peak of the merging epoch ($z \simeq 1-2$) is very rich: some resemble the cosmological parameters H_0 , Ω , ρ_0 , w , and Λ , resp.

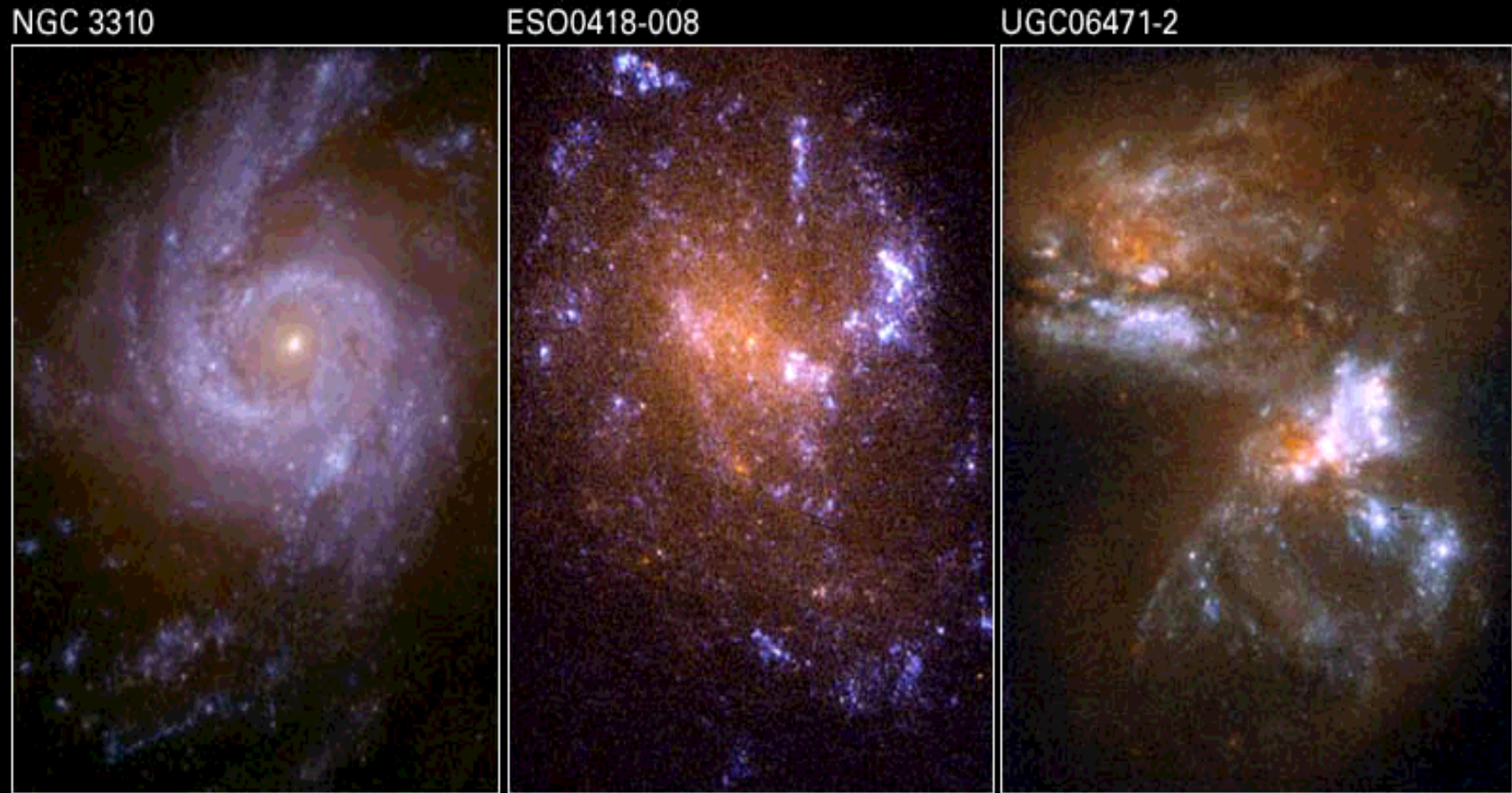


Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure.

(Rutkowski et al. 2010) \implies “Red and dead” galaxies aren’t dead!

- JWST will observe all such objects from 0.7–29 μm wavelength.

(6) Predicted Galaxy Appearance for JWST at $z \simeq 1-15$



Ultraviolet Galaxies

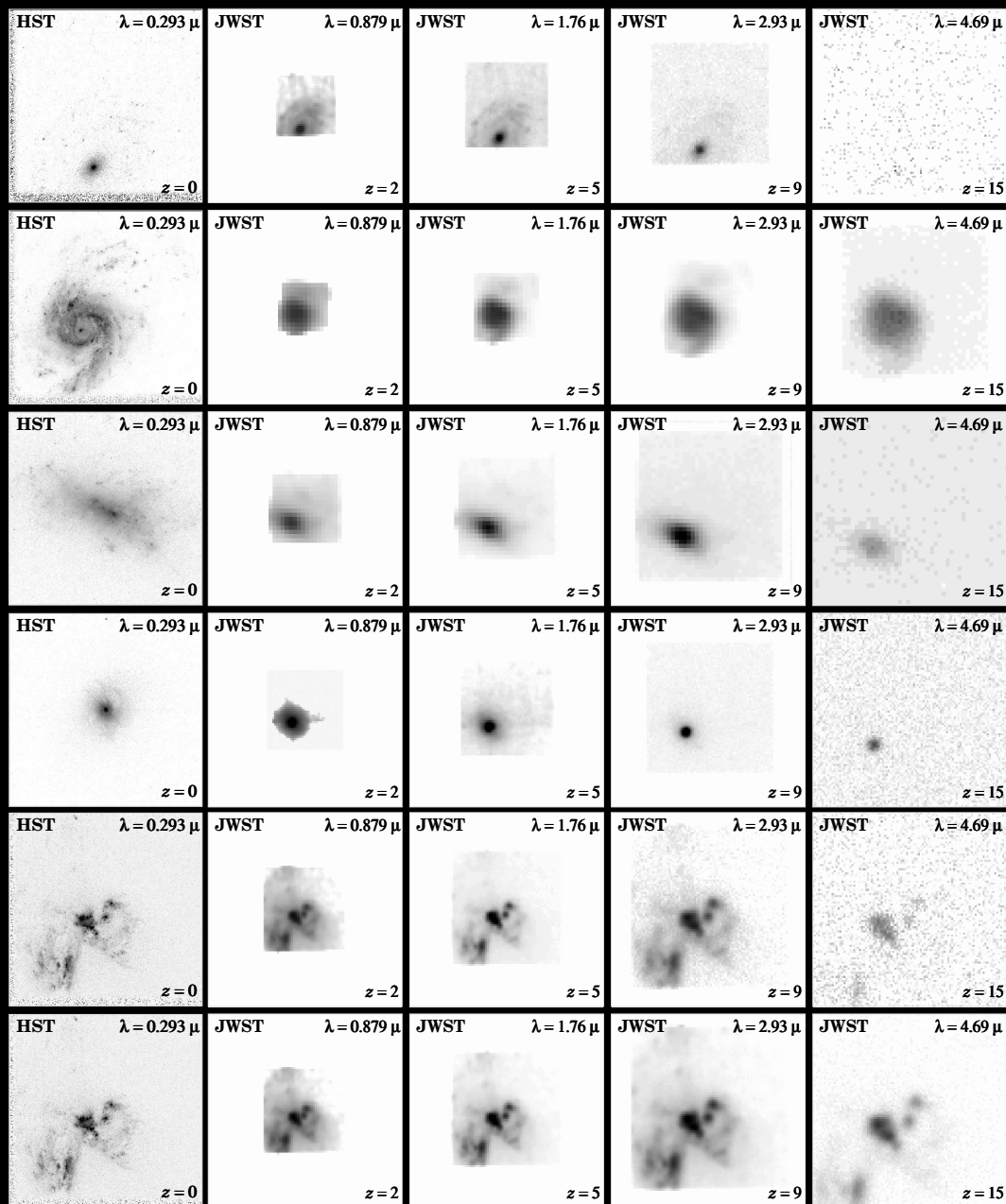
NASA and R. Windhorst (Arizona State University) • STScI-PRC01-04

HST • WFPC2

- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often copious amounts of dust imprinted.
- High-resolution HST UV images are benchmarks for comparison with very high redshift galaxies seen by JWST, enabling quantitative analysis of the restframe- λ dependent structure, B/T, CAS, SFR, mass, dust, etc.

(6) Predicted Galaxy Appearance for JWST at $z \simeq 1-15$ (w/ C. Conselice)

HST $z=0$ JWST $z=2$ $z=5$ $z=9$ $z=15$



With proper restframe UV-optical benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

- (1) Most disks will SB-dim away at high z , but most formed at $z \lesssim 1-2$.
- (2) High SB structures are visible to very high z .
- (3) Point sources (AGN) are visible to very high z .
- (4) High SB-parts of mergers/train-wrecks, etc., are visible to very high z .

- References and other sources of material shown:

<http://www.asu.edu/clas/hst/www/jwst/> [Talk, Movie, Java-tool]

www.asu.edu/clas/hst/www/ahah/ [Hubble at Hyperspeed Java-tool]

http://wwwgrapes.dyndns.org/udf_map/index.html [Clickable HUDF map]

<http://www.jwst.nasa.gov/> and <http://www.stsci.edu/jwst/>

http://jwst.gsfc.nasa.gov/faq_scientists.html

<http://ircamera.as.arizona.edu/nircam/>

<http://ircamera.as.arizona.edu/MIRI/>

<http://www.stsci.edu/jwst/instruments/nirspec/>

<http://www.stsci.edu/jwst/instruments/guider/>

Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

Windhorst, R., et al. 2007, Advances in Space Research, 42, p. 1965
(astro-ph/0703171) “High Resolution Science with High Redshift Galaxies”